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TURBINE ENGINE COMPRESSOR FLOW LIMITING

S. E. Arnett

The Bendix Corporation
Energy Controls Division

TECHNICAL REPORT AFAPL-TR-72-72

August 1972

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Air Force Aero Propulsion Laboratory
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Most current controls rely on an open-loop schedule of fuel to avoid compressor stall during acceleration and deceleration of the rotor or rotors. This program which is an extension of an investigation reported by Technical Report AFAPL-TR-71-78 is directed toward closed loop fuel control by sensing pressure relationships at the engine compressor discharge. The control signal was obtained by a special fluidic pressure ratio sensor utilizing the burner wall static pressure and a pressure obtained by a static probe in the last stator vane row.

The technique of acceleration and deceleration control was demonstrated on a J85-7 engine at APL. The control incorporates speed control with selection of engine speed used as the input request. An existing hydromechanical fuel unit with a torque motor input and valve position feedback was used to control fuel. Compressor geometry control was obtained by incorporating an electro-magnetic servo valve in the hydraulic lines to the actuators and by installing a position sensing potentiometer. The IBM 1800 computer installed in the Propulsion Laboratory was utilized to compute the desired valve position or change in valve position and geometry position. The system incorporates signal pickups and signal conversion devices. A support system designed and constructed including the conversion devices has a sufficient degree of flexibility to accomplish meaningful engine demonstrations.

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TURBINE ENGINE COMPRESSOR

FLOW LIMITING

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FOREWORD

This document is the final report of a four-month program starting March 1972, to determine the feasibility and the general applicability of fuel flow control by sensing the airflow conditions at the discharge of the engine compressor. The work is authorized by Air Force Contract F-33615-72-C-1710 PR9398, Project 3066. The work is monitored by the Air Force Aero Propulsion Laboratory of the Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, and directed by Mr. Richard High of the Turbine Engine Components Branch. The program is being conducted by the Propulsion Controls Engineering Department of Energy Controls Division of The Bendix Corporation, South Bend, Indiana.

The engine test work reported in this document was performed at WPAFB in cooperation with monitoring project engineers, and other personnel in the Aero Propulsion Laboratory at that facility.

This report covers work started in March 1972 continuing through June 1972 and was published in August 1972.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Ernest C. Simpson

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Current trend in turbo-gas generator control systems is toward greater use of electronic computer techniques in the control computations. With the increased use of electronics, some greater degree of flexibility in computation can be incorporated, and more signals and greater complexity of control modes appear possible with less weight and size penalty than appears feasible with the more conventional hydromechanical control.

Most current controls rely on an open-loop schedule of fuel to avoid compressor stall during acceleration and deceleration of the rotor or rotors. This program which is an extension of an investigation reported by Technical Report AFAPL-TR-71-78 is directed toward closed loop fuel control by sensing pressure relationships at the engine compressor discharge. The control signal was obtained by a special fluidic pressure ratio sensor utilizing the burner wall static pressure and a pressure obtained by a static probe in the last stator vane row.

The technique of acceleration and deceleration control was demonstrated on a J85-7 engine at APL. The control incorporates speed control with selection of engine speed used as the input request. An existing hydromechanical fuel unit with a torque motor input and valve position feedback was used to control fuel. Compressor geometry control was obtained by incorporating an electro-magnetic servo valve in the hydraulic lines to the actuators and by installing a position sensing potentiometer. The IBM 1800 computer installed in the Propulsion Laboratory was utilized to compute the desired valve position or change in valve position and geometry position. The system incorporates signal pickups and signal conversion devices. A support system designed and constructed including the conversion devices has a sufficient degree of flexibility to accomplish meaningful engine demonstrations.

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SECTION I

INTRODUCTION AND SUMMARY

The primary goal of this program is the demonstration of an engine acceleration-deceleration mode utilizing changes in compressor discharge variables between steady state and acceleration conditions and between steady state and deceleration conditions. Secondary goals include:

- Utilization of a commercial computer as a control development tool.
- Utilization of a rather simple fuel control unit with the commercial computer.
- Effects of compressor bleed position on the compressor discharge airflow parameter into engine stall.

The effort was divided between:

- Control system component procurement and fabrication.
- Computer programming.
- System Evaluation Tests.
- J85 engine tests.

Analyses of test data demonstrate that a relationship of pressures at or near the compressor discharge changes between steady state and transient conditions, and that a sense of the change can be used for fuel control during acceleration and deceleration transients. The allowable change in the sensed relationship depends on the compressor geometry schedule.

BACKGROUND

Historically, turbo-gas generators have been accelerated by some schedule of fuel flow based on variables indicative of airflow and engine operating point. The variables used have evolved over the years. The variable selection has been greatly

influenced by control hardware implementation. With the greater use of fluidic and electronic devices, a re-evaluation of variables is desirable.

Engine speed and some form of air density were used in early day control systems for fuel control inputs. Margins between steady-state operation and stall were rather large, and simple modes of control were feasible. Current engines have small margins between steady state and stall and require rather complex fuel control modes. To achieve accurate control it appears desirable to close the loop utilizing some parameter indicative of compressor operation.

Pressure relationship of the corrected airflow at the discharge of the compressor appears to be a usable parameter. The engine airflow decreases with increased compressor discharge restriction at low speed and the compressor discharge pressure rises with small change in airflow at high speed operation. Throughout the speed range, from idle to maximum, there exists a decrease in corrected airflow at the compressor discharge during engine accelerations and an increase in the corrected airflow during decelerations.

CORRECTED AIRFLOW PARAMETER

The corrected airflow parameter at the compressor discharge had been computed from compressor data during the previous program. The variation in the parameter has been found to be a function of pressure ratio of the compressor and the air bleed and/or variable stator characteristics. Low pressure ratio compressors have an airflow parameter which increases with speed. All compressors when operating at low pressure ratios have this characteristic. Intermediate pressure ratio compressors have an increasing airflow parameter up to some speed and then a decreasing characteristic. If these compressors are equipped with bleeds or variable stators, the parameter will be nearly constant in the normal operating speed range. High pressure ratio compressors will have bleeds, variable stators and/or two rotors, and the airflow parameter will tend toward a constant value.

The J85 engine exhibits a near constant value of the airflow parameter at the stall line of the compressor map and a constant value of the parameter can be used for control mode evaluation test.

CORRECTED AIRFLOW PARAMETER SENSING

The corrected airflow is a combination of flow rate, the temperature, and the pressure. The parameter is not directly sensed but is inferred by sensing other variables. The corrected flow per unit area, which might be expressed as $W_a\sqrt{\Theta}/\delta A$ or $W_a\sqrt{T}/PA$ with the units in any compatible system, is a function of

flow Mach number. Mach number is a function of total and static pressures at the point. The airflow parameter can then be reduced to a sense of pressures. Ideally, the pressures sensed, would be the total and static pressure at the point of investigation. Any two pressures can be used providing a correlation between the flow and the pressure can be established. The corrected flow based on total temperature and total pressure from the last rotor to air bleedoff or combustion is nearly constant. Total pressure may decrease due to turbulence, but this loss is small. The static pressure varies with the flow area. A static pressure at a large cross-section area is directly related to the average total pressure and can be used in combination with a static pressure at some smaller cross section to indicate flow.

In the area immediately behind the last stator and straightening vanes of the J85-7 engine, the flow Mach number may be as low as 0.25 at stall and as much as 0.40 at steady state. This variation would correspond to a pressure difference between static and total of 4.5 to 11 percent of the total pressure. Engine data have indicated that the total pressure in this area may vary along a radius by as much as four percent. Since the static pressure is relatively constant radially, the flow must vary from point to point. This variation is of the same order as the change from steady state to stall. In order to use a pressure signal that has a change of only 4.5 percent, an extremely accurate sensor is required. To aid in obtaining suitable signal strength, signal amplification by both probe design and sense location in the compressor discharge was investigated during the previous program.

Engine tests were run during that program to establish sensing techniques, relative values of variables for control design, and to determine operation of the sensing unit. A sensitive signal was obtained by using the compressor discharge wall static pressure and a pressure obtained by a spherical ended probe located in the rear stator vanes.

The sensor unit ($\Delta P/P$ sensor) was developed during another program and modified slightly for this program. The change in output of the sensor from steady state to acceleration or deceleration conditions is sufficient for control as demonstrated by the engine tests.

COMPUTER SIMULATION

Computer studies during the previous program were divided into two general investigation techniques. First, the engine and control were represented on the Bendix IBM 360-44 digital computer and initial control requirements were established. Second, the engine was simulated on the Bendix Pace Analog computer and the control was programmed for the digital computer.

The computer work yielded insight into system requirements and necessary operational characteristics for successful engine tests. Nominal gains for the control loops were established. Tolerable computer solution time was investigated.

A third engine simulation was made for use with the IBM 1800. This simulation and adjustments were used at APL to test the computer program before engine running. A new checkout computer program for engine simulation was established for the AFAPL Pace TR-48 analog computer. The interface package was designed to allow use of the Pace signals through the interface by connecting a cable to the package. Although the program did not ideally simulate the engine, all fuel control loops could be checked for operation before engine running.

CONTROL SYSTEM CONFIGURATION

The control system is composed of an electronic package, IBM 1800 computer, sensors, fuel valve, and compressor bleed and guide vane control.

Sensors on the engine are:

- Two compressor discharge pressure transducers
- One differential pressure transducer
- Pressure ratio sensor
- Magnetic electrical pulse speed signal
- Turbine temperature sensor (not part of program but provisions for use are included in the control)
- Bleed position transducer

The bleed and guide vane control includes:

- Selection valves
- Servo valve
- Actuators and linkages
- Position potentiometer

The fuel valve element includes:

- Metering valve
- Power lever potentiometer for speed selection input
- Metering valve position potentiometer
- Bypass valve
- Torque motor for valve modulation

The electronic package includes:

- Schedule trim potentiometers
- Position controls
- Sensor circuits
- Power supplies
- Speed demodulator circuits

Computations for the desired fuel valve position (fuel flow) and/or the compressor bleed position are accomplished by the IBM 1800 computer program. The computations include the following:

- Engine start cycle
- Engine acceleration cycle on the airflow parameter or a fuel flow schedule
- Engine deceleration on the airflow parameter or a fuel flow schedule
- Speed governing
- Burner pressure control
- Turbine temperature control
- Compressor bleed and guide vane schedule

ENGINE CONTROL SYSTEM TESTING

Tests of the system were successfully accomplished at APL on the J85-7 engine. Only minor problems were encountered during system installation, checkout, and engine operation. The engine was successfully accelerated and decelerated by use of the airflow (pressure ratio) parameter. The parameter was used to control the rate of change in fuel request and also to proportionally control the request. The rate control was most successful during both acceleration and deceleration tests. The engine was stalled by off scheduling the compressor bleeds at 70 and 75 percent speed. No change indicative of impending stall was obtained from the sensor and the sensor output indicated a more safe condition after the stall. The results of the demonstration are presented in Section V.

SECTION II

SYSTEM DESCRIPTION

The system is composed of engine, sensors, electronic interface, IBM 1800 computer, instrumentation, plumbing, cabling and checkout equipment. Figure 1 represents the system arrangement in block form. Engine sensors and control elements are connected to the interface package by eighty feet of cable. The interface is connected to the computer terminal by twenty feet of cable and the terminal is about 100 feet from the computer. The checkout Pace computer is connected to the interface by forty feet of cable. Figure 2 is a block diagram illustrating the engine plumbing and instrumentation. Engine fuel flow can either be from the parts list control or from the parts list pump through the EH-G1 control. Similarly, the bleed actuator flow can be from either source of control. Also both the fuel flow and bleed control flow can be from an auxiliary pump for checkout of the control loops. Engine Data was recorded by an eight channel strip recorder and by a "B" size X-Y plotter.

ENGINE FUEL FLOW PLUMBING

Figure 3 illustrates the fuel plumbing used to obtain flexibility in checkout and operation of the system. The valving allows for operation on either the engine pump or an auxiliary pump. The engine can be run on the engine pump and control and the computer program can be checked out by use of the auxiliary pump loop. Start fuel flow is rather low during engine starting. The two check valves are incorporated in the system to allow use of the auxiliary pump for bleed control during the starting sequence. A pressure relief valve is incorporated in the EH-G1 bypass line as a safety feature.

The fifteen (15) valves plumbed into the fuel system are manipulated for various modes of operation as listed in Table 1. Valve number 2 is set to obtain the desired nominal pressure for operation of the system. When the EH-G1 control is being checked for operation the bypass valve operates to maintain the required pressure for control operation. During bleed control operation, the valve is set to prevent over pressurizing with no flow through the servo system; During auxiliary pump assisted starts, Valve 2 is set to yield sufficient pressure for ignition flow through the nozzles with the bypass valves shut. Then with the bypass valve operating, the required engine pressure excedes the auxiliary pump pressure and the check valves close.

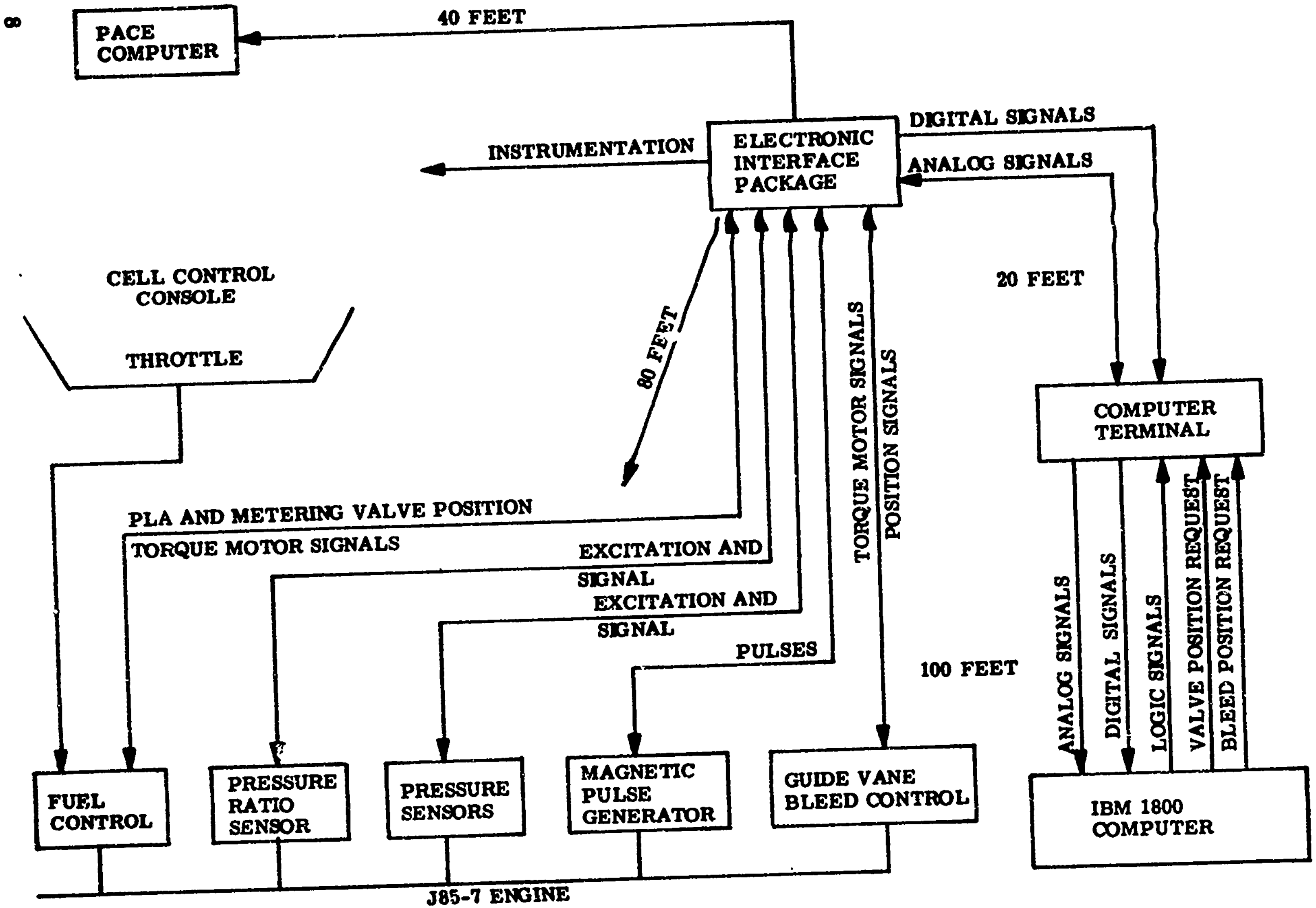

Figure 1 -- Block Diagram of System Arrangement

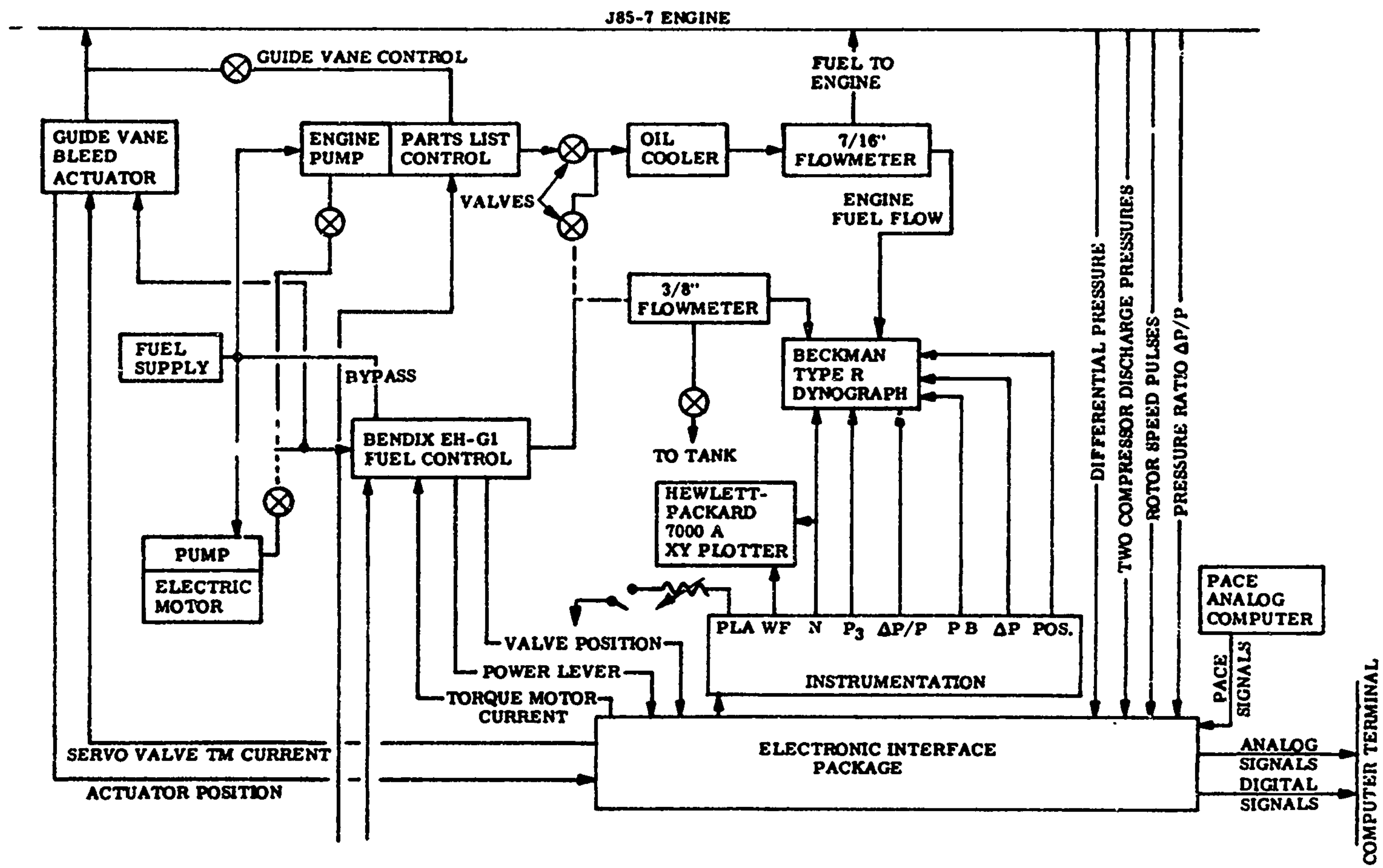

Figure 2 -- Block Diagram of Plumbing & Instrumentation Concepts

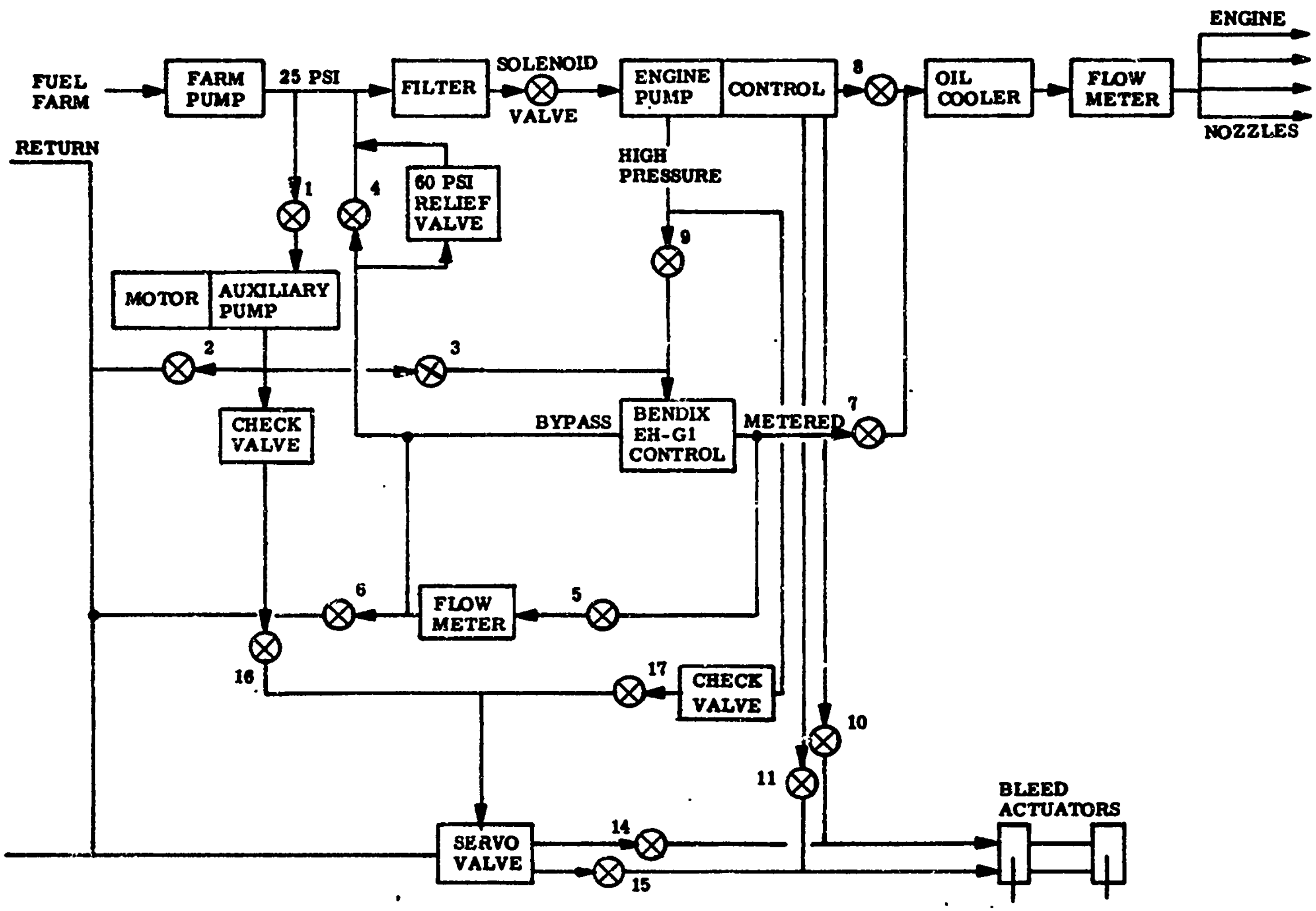

Figure 3 -- Fuel System Plumbing

OPERATING MODE	VALVE NUMBER 1	2	3	4	5	6	7	8	9	10	11	14	15	16	17
Parts List System		S						8		10	11				
Parts List Pump															
Nozzle Flow EH-G1		S		4			7		9						
Bleed Control Parts List										10	11				
Parts List Pump															
Nozzle Flow Part List		S		4				8							
Bleed Control Servo Valve												14	15		17
Parts List Pump															
Nozzle Flow EH-G1		S		4			7		9						
Bleed Control Servo Valve												14	15		17
Auxiliary Pump Checkout															
Nozzle Flow EH-G1	1	S	3		5	6									
Bleed Control Servo Valve	1	S										14	15	16	
With Engine Running	1	S	3		5	6		8		10	11				17
Nozzle Flow Parts List								8							
Auxiliary Pump Servo Valve	1	S										14	15	16	
Auxiliary Pump Start															
Nozzle Flow EH-G1				4			7		9						
Bleed Control Servo Valve	1	S										14	15	16	17

"Number" means valves open
"S" set as required
All other valves closed

Table 1 -- Engine Fuel System Valve Settings

ELECTRONIC INTERFACE PACKAGE

As shown by Figures 1 and 2, all system signals are to and from the interface. The interface circuits are contained in a 19 x 20 x 62 inch rack.

Figures 4 and 5 show the front and rear views of the package. Rack features from bottom to top are:

- Two 8.75" storage drawers,
- Power supplies for ±5, ±15, and 0-34 VDC,
- A convenience shelf,
- An 8.75" spare space,
- The EK15 circuit assemblies, and
- The EK14 chassis.

The package is connected into the control system by cables through the connectors shown by Figure 5. The EK14 chassis was constructed during the program of Reference 1 and has been incorporated into the rack. Details of the interface package are presented in Appendix A.

CABLING

Figure 6 is a block diagram illustrating the inputs to and the outputs from the interface. Signal conditioning from input to output is accomplished by the various package circuits. A voltmeter, shown by Figure 4, is included in the package for monitoring the various adjustments and signals. Significant features include:

- Adjustments to the IBM 1800 computer program by voltage settings of potentiometers,
- Speed or frequency converters to provide both digital numbers proportional to the reciprocal of frequency and voltages proportional to frequency.

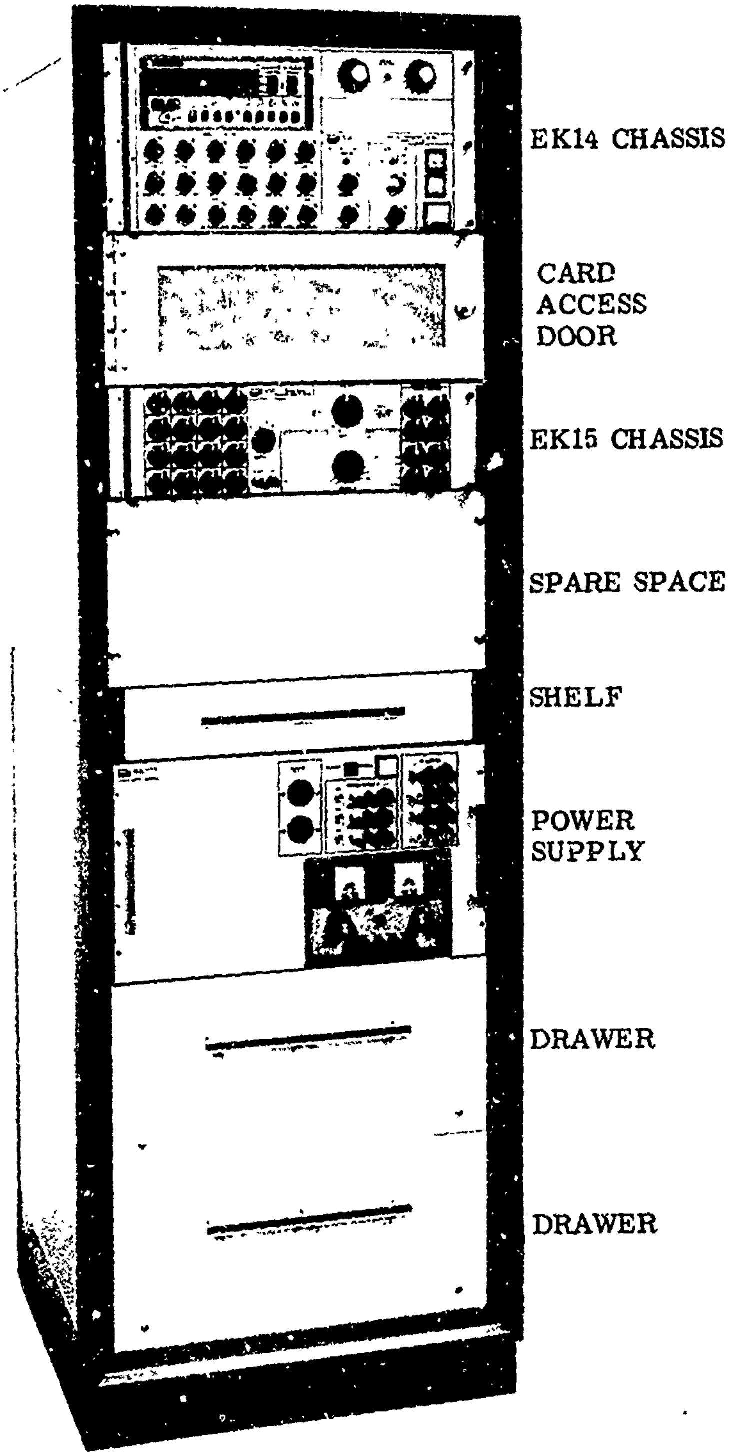

Figure 4 -- Front View of Interface Rack

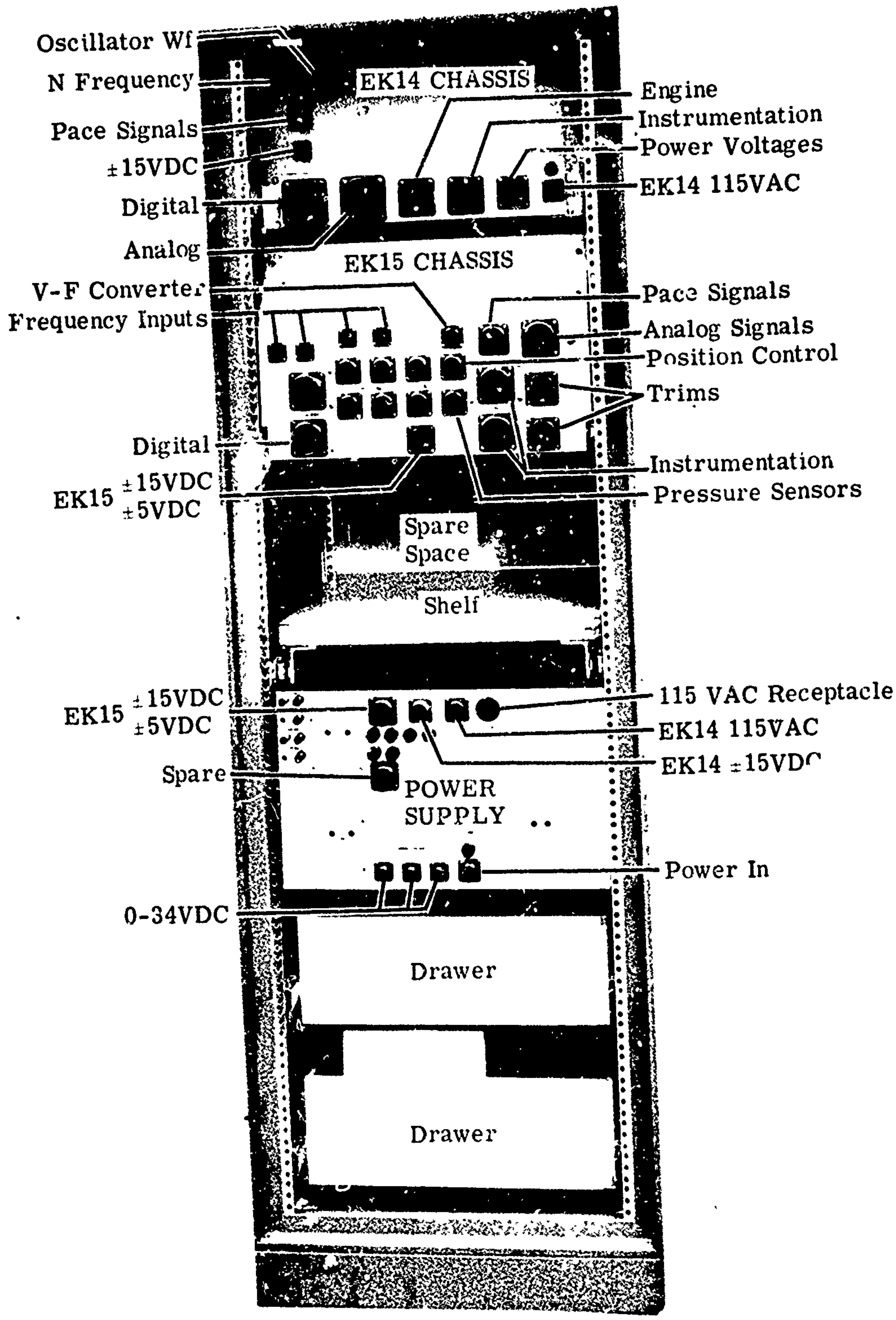

Figure 5 -- Rear View of Interface Rack

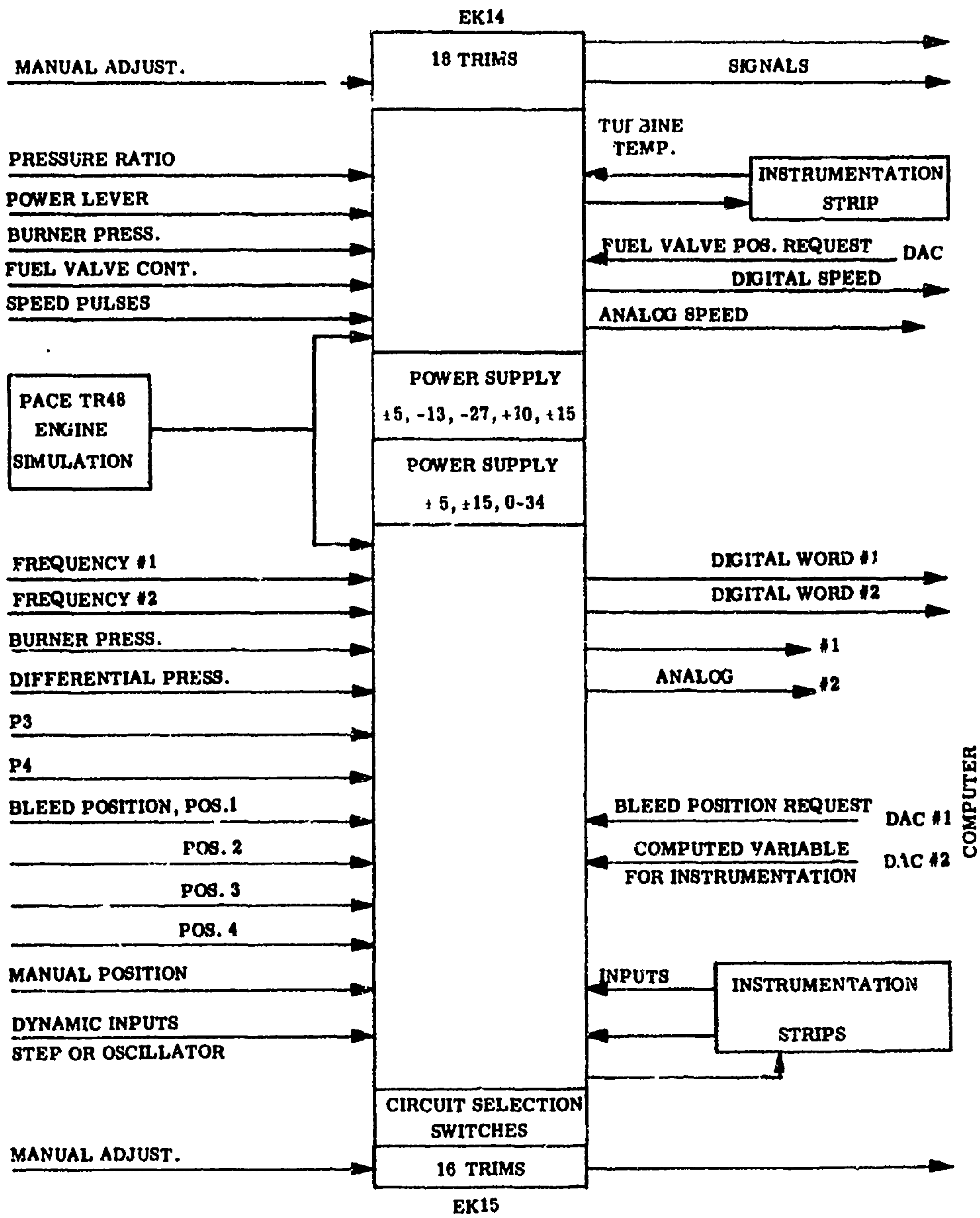

Figure 6 -- Inputs and Output of Interface Circuits

- Five strain gage type pressure transducer circuits.
- Five position control circuits through torque motor driver amplifiers. These include the fuel valve control and the compressor bleed control.
- One pressure ratio sensor circuit.
- Provisions for computer program checkout by use of the Pace Analog computer.
- Three instrumentation strips for use at recorders. These strips contain provisions for three signal inputs to the computer.
- Power supplies.
- Dynamic inputs (an oscillator input) to the fuel valve and bleed control circuits and a step to the bleed control circuits.
- Circuit selection switches.

The system requires a 115 volts 60 cps input line to the EK15 power supply. This line is unfused to an output to the EK14 assembly and to three utility receptacles for auxiliary test components such as meters and an oscillator. The line is fused to the D.C. voltage power supplies which consist of ±5, ±15 and a variable 0 to 34 VDC. System cables are:

- Interrack
  - AC power to EK14,
  - ±15 VDC to EK14,
  - ±15 and ±5 (one cable) to EK15 card chassis, and
  - Voltmeter connection.
- Engine
  - One multiple cable between the EK14 chassis and the fuel control, pressure ratio sensor, pressure sensor, and pulse pickup.

- Two cables between the EK15 card chassis and a burner pressure sensor and a differential pressure sensor.

- One multiple cable between the EK15 chassis and the bleed control servo and the bleed position transducer.

- One coaxial cable, the use of which is not defined.

- Instrumentation

  One strip to the EK14 and two strips to the EK15 card chassis.

- Trim Signals

  Two fanning strips attached to one connector at the EK14 and two fanning strips attached to two connectors at the EK15 card chassis. Instrumentation inputs are included in trim cable #2 of the EK15 chassis.

- Digital Words

  One word for engine speed from the EK14 chassis and two words from the EK15 card chassis.

- Variable Signals

  Four signals from the EK14 chassis through the same connector as the trims and eight signals from the EK15 chassis through a separate connector.

- Pace Computer

  One cable to the EK15 card chassis with a jumper cable to the EK14 chassis.

- Voltage to Frequency Converter

  One cable from the EK15 card chassis to a converter and a frequency input cable for attachment to the various frequency inputs.

● Oscillator Input

One cable for fuel valve oscillator input to the EK14 fuel control circuit and one cable to the EK15 position control circuits.

ANALOG COMPUTER PROGRAM

An analog computer program was prepared for use in checkout of the IBM 1800 control program without engine running. The program illustrated by the block diagram of Figure 7 contains a minimum of dynamics and loops and thus does not represent the engine and sensor ideally. The representation is sufficient for the purpose. Equations used to generate the signals and the signal output magnitudes are shown by Figure 7.

The valve position request is fed in from the IBM 1800 computer. The fuel valve is represented by an integration with fuel output being proportional to valve position. This fuel is compared to the required to run fuel which is generated in a function box. The differential fuel thus obtained is the dynamic input to the simulated engine.

Rotor acceleration is proportional to the differential fuel and proportional to rotor speed. The acceleration is integrated to yield the rotor speed. The speed is fed back to the IBM 1800 computer where it is compared with the power lever requested speed. This comparison and 1800 computer program effects the requested valve position and closes the loop on speed.

The speed is used in a second function generator to provide a steady state temperature reference. The differential fuel flow is used to compute a differential temperature which is greater or less than steady state temperature depending on whether the differential fuel flow is greater or less than steady state. Addition of the steady state temperature and the differential temperature yields the engine temperature.

Temperature and speed are used in an adder circuit to generate the burner pressure. A differential pressure equal to the burner pressure minus the static pressure in a high velocity proportion of the blading is set equal to 0.2 the burner pressure modified by the differential temperature value.

The value of $\Delta P/P$ sensor in pressure values is assumed to be .2 modified by the differential temperature value.

Final gain constants are shown to convert the computed signals to voltage signals of proper magnitude for input to the computer.

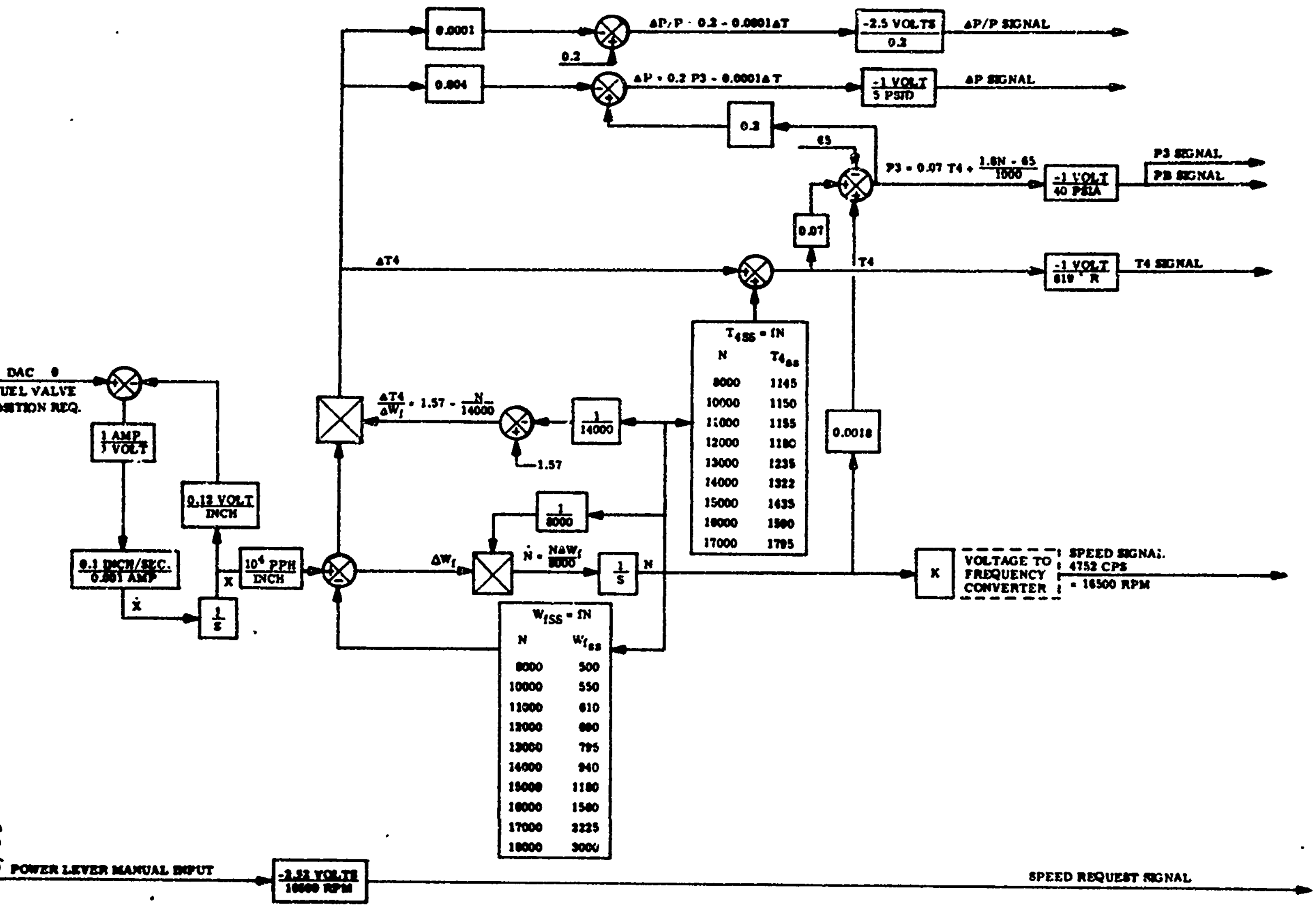

Figure 7 -- Block Diagram of Engine Simulation

SECTION III

CONTROL PROGRAM DESCRIPTION

The control program includes several loops which can be used independently for control during some phase of engine operation or in conjunction with other loops during a phase of operation. Some of the loops included were not required by contract but were included to ascertain feasibility of the loop if time permitted. IBM 1800 computer program time was increased about 1 millisecond by the additional computational cycle time. The program is represented by the block diagram of Figure 8. The computation listing is presented in Table 2. Figures 9 through 13 illustrate the various control loops separated out from the total program for clarity.

Adjustment to the computer program is by voltage settings of potentiometers. Eighteen (18) of these trim potentiometers were included in the Bendix EK14 interface package. Sixteen (16) more trim potentiometers were added by the EK15 interface package. These voltages are converted by an A to D converter over the range from -5 volts equal 32767 counts to +5 volts equal -32767 counts. Only negative voltages are used for both the trims and engine variables. The engine speed is input by a digital word proportional to the reciprocal of speed. Computer counts for speed are equal in magnitude to the engine rpm. Outputs from the program are through D to A converters from 32767 counts equal 10 volts to -32767 counts equal -10 volts.

UNITS AND CONVERSIONS

It is often convenient as an aid to understanding to attach equivalent engineering units to the abstract computer counts. Various equations in the description relates engineering units to voltages to computer counts to obtain an insight into the effects of the various points in the computation sequence. Engineers accustomed to working with turbo jet engine controls often speak and think in terms of ratios. The ratios being the term fuel flow in pounds per hour divided by burner pressure in pounds per square inch absolute. The magnitude of ratios depends on the size of the engine. For any one engine it is convenient to express operation in terms of ratios. The steady state ratio and the acceleration ratios are variable with compressor inlet temperature and to a small extent with pressure and speed. For the J85-7 the steady

state ratios in the speed range from 65 percent to 100 percent in the AFAPL test cell during the summer time is very near 20 ratios. With computer scaling used, one ratio is very near 32.8 counts. Thus Trim 9 which is designated base ratios is set at -1.6 volts to yield 657 counts by the computation $-1.6 \times 32767/(-5) \times 2^4 = 657$ counts. Any number which appears in the select high and select low computation then has a relationship to ratios or steady state ratios or number depending on the magnitude of the number.

Count values in other parts of the fuel loop depend on the multipliers associated with the computational path. Multiplications are affected by gain numbers. The gain numbers are set by potentiometers. Thus a count in the speed control path has an equivalent ratio effect depending on the gain potentiometer setting. A count in the speed circuit is equal to one rpm. The ratios count effect of one rpm is then equal to one rpm x volts of Trim 6 x $32767/5 \times 2^{14}$ = .4 volts of Trim 6 x rpm. Thus at 2.5 volts of Trim 6 an rpm is equivalent to one ratios count or 32.8 rpm is equivalent to one ratio.

FUEL-PRESSURE RATIOS BOUNDS

Figure 9 illustrates computations which bound the fuel flow in terms of ratios. Closed loop control operates within the bounds set by these computation paths.

Deceleration ratios are set by Trim 5. Computer counts of this trim are 51 counts/volt. Since there is a maximum of 5 volts, the maximum counts are 256. To this number is added the closed loop deceleration counts which is a maximum of 350. Since the minimum voltage of Trim 5 is 1.66, the program count is in the range 606 to 85 counts. These numbers are 15 to 2.6 ratios. This part of the control is the minimum possible ratios and must be maintained below the required to run ratios or the speed control would be ineffective.

The maximum ratios obtained at any speed are determined by select low logic of three schedules. At low speeds the maximum ratios are determined by the zero speed intercept (Trim 17) plus the speed slope factor (Trim 18). The equation of this line is: counts= (Volts of Trim 17) 205 + (Volts of Trim 18) 205 x rpm/2^{13}.

Nominal settings of these trims are 1.5 volts and 2.69 volts, respectively. Thus the intercept is 308 counts and 9.4 ratios. The slope adds to this such that at 12.8 percent speed, 144 counts are added and at 51 percent speed 576 counts are added to the intercept. Total ratios are then 13.8 and 26.9.

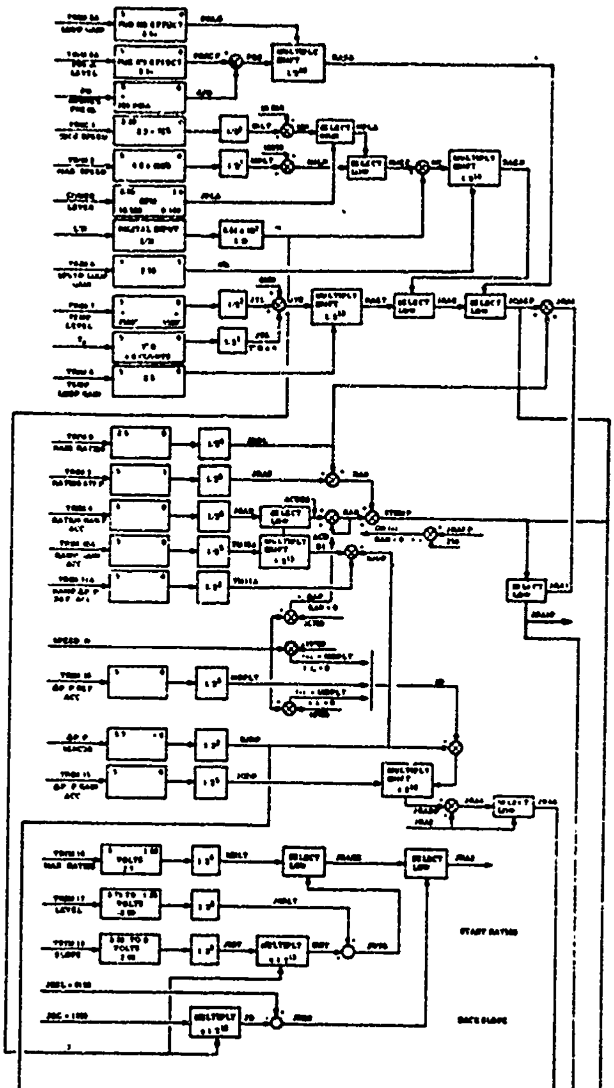

Figure 8--Diagram of Computer Control Program

23.1

23.2

23.3

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for greater detail.
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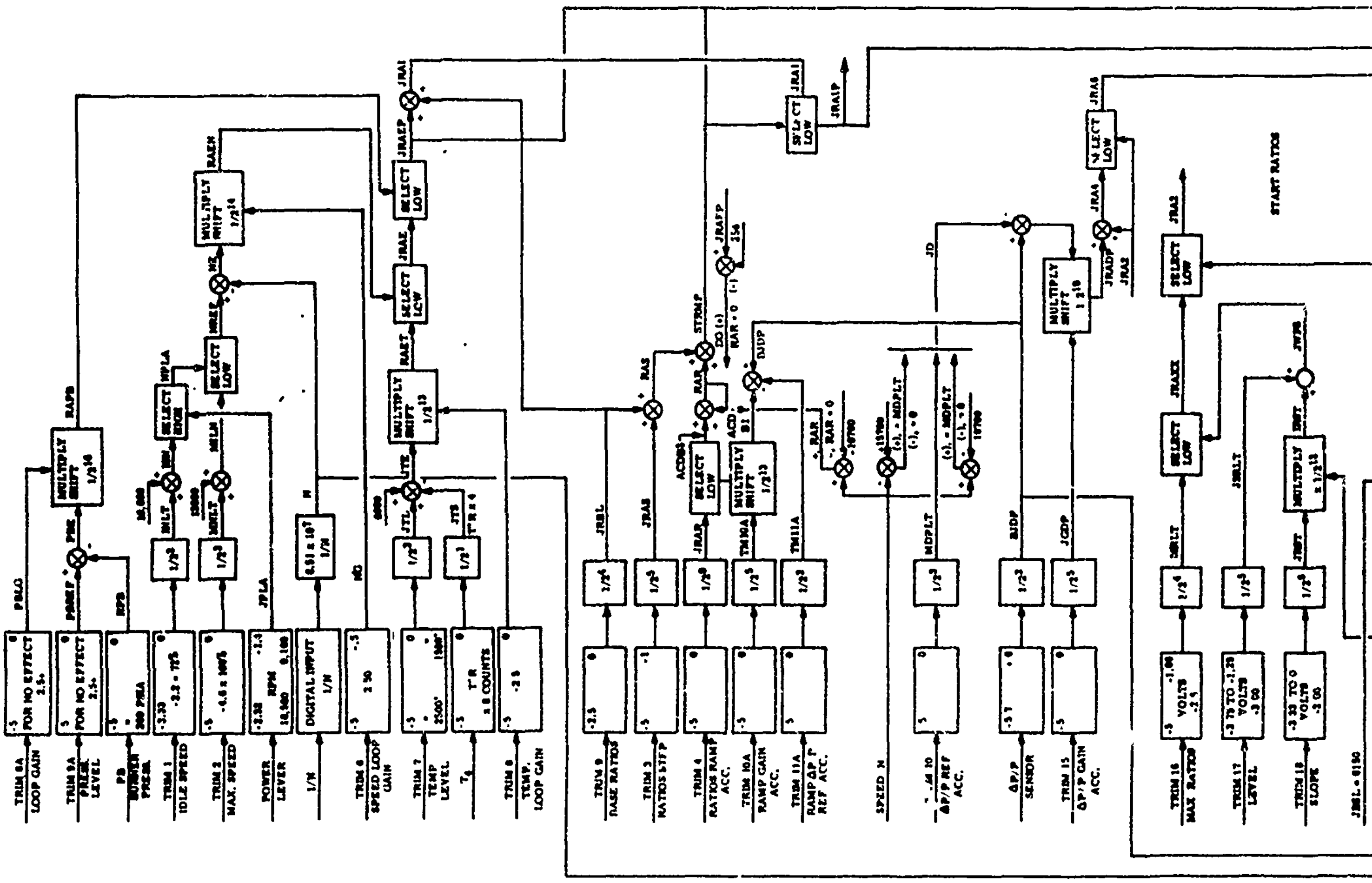
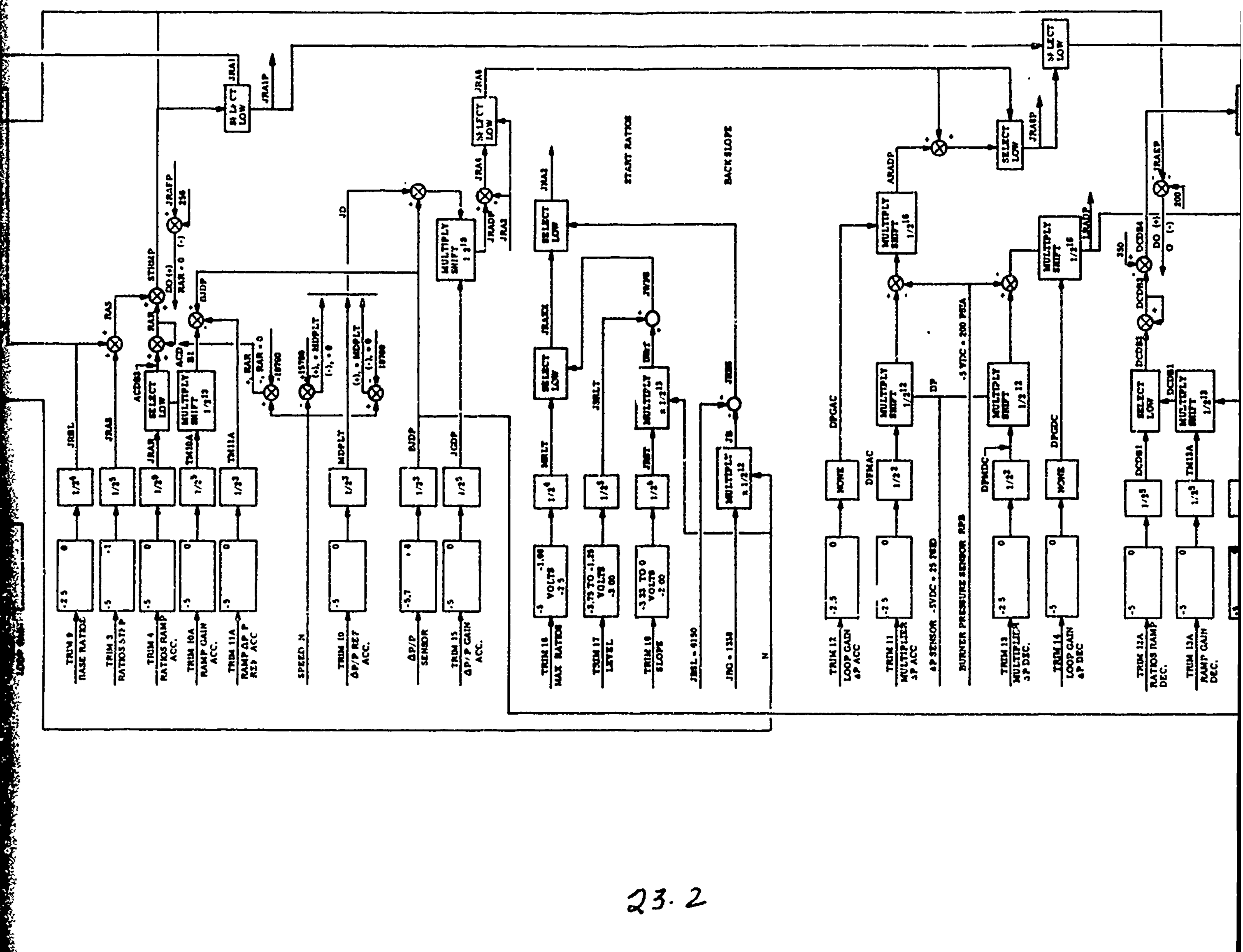


23.1

23.2



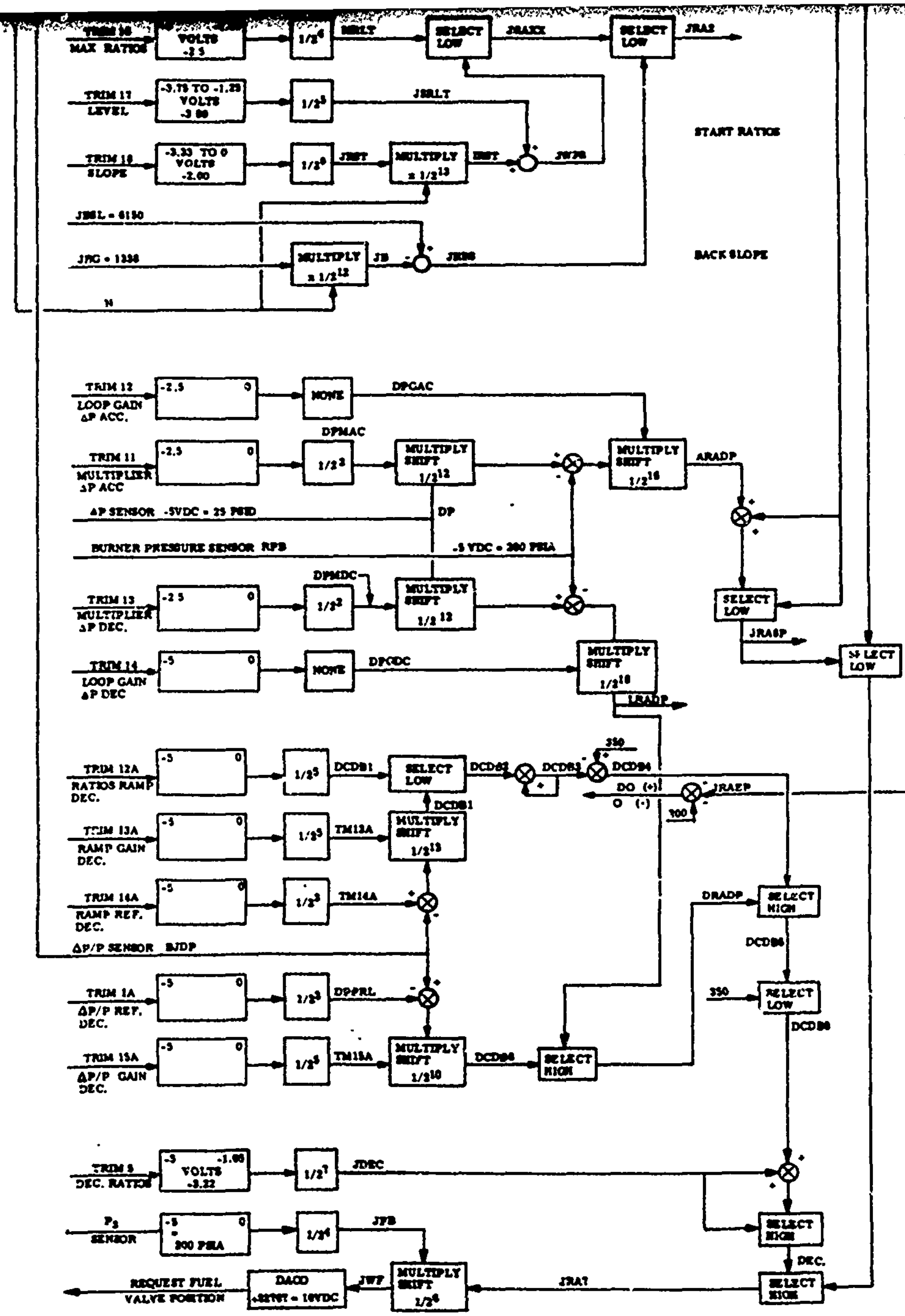


Figure 8--Diagram of Computer Control Program

```
008E 01 74FF0005             MDX      TESTN,-1
0090 0  70FA                 B        GETN
                       *
                       *  INSERT CODING HERE TO TAKE ACTION
                       * IF RPM DIGITAL WORD IS NOT VALID FOR 5 TRIES
                       *
                       *
                       *
0091                   VALID EQU      *
0091 0  D1E7                 STO    1 RAWN-L
0092 0  E044                 AND      =/7FFF
0093 01 D4000003             STO  L   TEMP1
0095 0  C8EC                 LDD      KSUBN
0096 0  1885                 SRT      5
0097 01 AC000003             D    L   TEMP1
0099 0  D1D1                 STO    1 PLOTN-L
009A 0  D2E1                 STO    2 N-C
                       *                              BACK SLOPE COMPUTATIONS
009B 0  C2E1                 LD     2 N-C
009C 0  A03B                 M        =1338
009D 0  1084                 SLT      4
009E 0  D1FF                 STO    1 JB-L
009F 0  C039                 LD       =6150
00A0 0  91FF                 S      1 JB-L
00A1 0  D1FE                 STO    1 JRBS-L
                       *                              START COMPUTATIONS
00A2 0  C2E2                 LD     2 JSRST-C
00A3 0  A2E1                 M      2 N-C
00A4 0  1083                 SLT      3
00A5 0  D1FD                 STO    1 IRST-L
00A6 0  82E3                 A      2 JSRLT-C
00A7 0  D1FC                 STO    1 JWPS-L
                       *  SLECT LOW
00A8 0  B2E4                 CMP    2 MRLT-C
00A9 0  C2E4                 LD     2 MRLT-C
00AA 0  1000                 NOP
00AB 0  D1FB                 STO    1 JRAAX-L
                       *  SELECT LOW
00AC 0  B1FE                 CMP    1 JRBS-L
00AD 0  C1FE                 LD     1 JRBS-L
00AE 0  1000                 NOP
00AF 0  D1FA                 STO    1 JRA2-L
                       *                              RPM COMMAND
00B0 0  C2F3                 LD     2 INLT-C          IDLE SPEED TRIM
00B1 0  8028                 A        =10000
00B2 0  D1F8                 STO    1 ISN-L
                       *
00B3 0  C2F2                 LD     2 MNLT-C          MAX SPEED TRIM
00B4 0  8026                 A        =13000
00B5 0  D1F7                 STO    1 MILN-L
00B6 0  C32E                 LD     3 P46PL-ISC
00B7 0  D2DF                 STO    2 JPLA-C
                       *  SELECT HIGH
00B8 0  B1F8                 CMP    1 ISN-L
00B9 0  7002                 MDX      *+2
00BA 0  1000                 NOP
00BB 0  C1F8                 LD     1 ISN-L
```


Table 2 -- Computer Computation Listing

```
00BC 0  D1F6              STO   1 NPLA-L
                      *   SELECT LOW
00BD 0  B1F7              CMP   1 MILN-L
00BE 0  C1F7              LD    1 MILN-L
00BF 0  1000              NOP
00C0 0  D1F5              STO   1 NREF-L
00C1 0  92E1              S     2 N-C
00C2 0  D1F4              STO   1 NF-L
00C3 0  A2EE              M     2 NG-C
00C4 0  1082              SLT     2
00C5 0  D1F3              STO   1 RAEN-L
                      *                          TURBINE TEMP COMPUTATION
00C6 0  C32F              LD    3 P47T4-ISC
00C7 0  1881              SRT     1
00C8 0  D2DE              STO   2 JTS-C
00C9 0  C2ED              LD    2 JTL-C          TEMP LEVEL TRIM
00CA 0  92DE              S     2 JTS-C          REAL T4
00CB 0  8010              A       =6000
00CC 0  D1F2              STO   1 JTE-L
00CD 0  A2EC              M     2 JTGL-C         TEMP GAIN TRIM
00CE 0  1083              SLT     3
00CF 0  D1F1              STO   1 RAFT-L
                      *   SELECT LOW
00D0 0  B1F3              CMP   1 RAEN-L
00D1 0  C1F3              LD    1 RAEN-L
00D2 0  1000              NOP
00D3 0  D1F0              STO   1 JRAE-L
                      *
00D4 0  7008              B       GO1
                      *   BREAK HERE
                          LORG
00D5 0  0032          +   DC      50
00D6 0  0005          +   DC      5
00D7 0  7FFF          +   DC      /7FFF
00D8 0  053A          +   DC      1338
00D9 0  1806          +   DC      6150
00DA 0  2710          +   DC      10000
00DB 0  32C8          +   DC      13000
00DC 0  1770          +   DC      6000
                      *   END BREAK
00DD 0  1000          GO1 NOP
                      *
                      *                          BURNER PRESSURE COMPUTATIONS
00DE 0  C331              LD    3 P49PB-ISC
00DF 0  D2DC              STO   2 RPB-C
00E0 0  C2F4              LD    2 PBREF-C        PRESSURE LEVEL TRIM
00E1 0  92DC              S     2 RPB-C
00E2 0  D1EF              STO   1 PBE-L
00E3 0  A2F5              M     2 PBLG-C         PRESSURE LOOP GAIN
00E4 0  1080              SLT     0
00E5 0  D1EE              STO   1 RAPB-L
                      *   SELECT LOW
00E6 0  B1F0              CMP   1 JRAE-L
00E7 0  C1F0              LD    1 JRAE-L
00E8 0  1000              NOP
00E9 0  D1ED              STO   1 JRAEP-L
00EA 0  82E8              A     2 JRBL-C
```


Table 2 -- Continued

```
00EB 0  D1EC              STO   1 JRA1-L
                    *  PRESSURES RATIO ACCELERATION CONTROL
                    *                              COMPUTE RATIOS STEP AND RAMP
00EC 0  C2F1              LD    2 JRAS-C
00ED 0  82EB              A     2 JRBL-C
00EE 0  D1EB              STO   1 RAS-L
00EF 0  C32D              LD    3 P45PP-ISC
00F0 0  1883              SRT     3
00F1 0  D2E0              STO   2 BJDP-C
00F2 0  9206              S     2 TM11A-C
00F3 0  D1CF              STO   1 ACDB1-L
00F4 0  A2L7              M     2 TM10A-C
00F5 0  1083              SLT     3
00F6 0  D1CE              STO   1 ACDB2-L
                    *  SELECT LOW
00F7 0  B2F0              CMP   2 JRAR-C
00F8 0  C2F0              LD    2 JRAR-C
00F9 0  1000              NOP
00FA 0  D1CD              STO   1 ACDB3-L
00FB 0  81EA              A     1 RAR-L
00FC 0  D1EA              STO   1 RAR-L
                    *
                    *  FOR ENGINE START ONLY
00FD 0  C2E1              LD    2 N-C
00FE 0  903C              S       =10700
00FF 01 4C300103          BP      ENGST
0101 0  C03A              LD      =0
0102 0  D1EA              STO   1 RAR-L
0103 0  1000        ENGST NOP
                    *  END ENGINE START ONLY
                    *
0104 0  C1ED              LD    1 JRAEP-L
0105 0  9037              S       =256
0106 01 4C30010A          BP      G02
0108 0  C033              LD      =0
0109 0  D1EA              STO   1 RAR-L
010A 0  C1EA        G02   LD    1 RAR-L
010B 0  81EB              A     1 RAS-L
010C 0  D1E9              STO   1 STRMP-L
                    *  SELECT LOW
010D 0  B1EC              CMP   1 JRA1-L
010E 0  C1EC              LD    1 JRA1-L
010F 0  1000              NOP
0110 0  D1E8              STO   1 JRA1P-L
                    *                             DELTA P LOOP COMPUTATIONS
0111 0  C02A              LD      =0
0112 0  D1F9              STO   1 JD-L
0113 0  C02A              LD      =15700
0114 0  92E1              S     2 N-C
0115 01 4C08011D          BNP     NOMID
0117 0  C2E1              LD    2 N-C
0118 0  9022              S       =10700
0119 01 4C08011D          BNP     NOMID
011B 0  C2EA              LD    2 MDPLT-C
011C 0  D1F9              STO   1 JD-L
011D 0  1000        NOMID NOP
011E 0  C2E0              LD    2 BJDP-C     DELTA P/P ACTUAL
```

Table 2 -- Continued

```
011F 0   91F9      338          S      1 JD-L
0120 0   A2E5      339          M      2 JGDP-C     DELTA P LOOP GAIN
0121 0   1086      340          SLT      6
0122 0   D1E6      341          STO    1 JRADP-L
0123 0   81FA      342          A      1 JRA2-L
0124 0   D1E5      343          STO    1 JRA4-L
                   344     *  SELECT LOW
0125 0   B1FA      345          CMP    1 JRA2-L
0126 0   C1FA      346          LD     1 JRA2-L
0127 0   1000      347          NOP
0128 0   D1E4      348          STO    1 JRA6-L
                   349     *                        DELTA P MULTIPLIER ACCEL
0129 0   C332      350          LD     3 P50DP-ISC
012A 0   D2DB      351          STO    2 DP-C
012B 0   A2E9      352          M      2 DPMAC-C    DIFF. PRESSURE TRANSDUCER
012C 0   1084      353          SLT      4
012D 0   92DC      354          S      2 RPB-C
012E 0   A2E8      355          M      2 DPGAC-C    ACCEL LOOP GAIN
012F 0   1080      356          SLT      0
0130 0   D1E3      357          STO    1 ARADP-L
0131 0   81E4      358          A      1 JRA6-L
                   359     *  SELECT LOW
0132 0   B1E4      360          CMP    1 JRA6-L
0133 0   C1E4      361          LD     1 JRA6-L
0134 0   1000      362          NOP
0135 0   D1E2      363          STO    1 JRA6P-L
                   364     *  SELECT LOW
0136 0   B1E8      365          CMP    1 JRA1P-L
0137 0   C1E8      366          LD     1 JRA1P-L
0138 0   1000      367          NOP
0139 0   D1E1      368          STO    1 JRA5-L
                   369     *
                   370     *   BREAK HERE
013A 0   7004      371          B        G03
                   372          LORG
013B 0   29CC      373     +    DC       10700
013C 0   0000      374     +    DC       0
013D 0   0100      375     +    DC       256
013E 0   3D54      376     +    DC       15700
013F 0   1000      377     G03  NOP
                   378     *   END BREAK
                   379     *  PRESSURE RATIOS DECELLERATION CONTROL
0140 0   C2D3      380          LD     2 TM14A-C
0141 0   92E0      381          S      2 BJDP-C
0142 0   A2D4      382          M      2 TM13A-C
0143 0   1083      383          SLT      3
0144 0   D1CC      384          STO    1 DCDB1-L
                   385     *  SELECT LOW
0145 0   B2D5      386          CMP    2 TM12A-C
0146 0   C2D5      387          LD     2 TM12A-C
0147 0   1000      388          NOP
0148 0   D1CB      389          STO    1 DCDB2-L
0149 0   81CA      390          A      1 DCDB3-L
014A 0   D1CA      391          STO    1 DCDB3-L
014B 0   C049      392          LD       =-200
014C 0   91ED      393          S      1 JRAEP-L
014D 01  4C300151  394          BP       DODEC
```

Table 2 -- Continued

```
014F 0  C0EC      395           LD        =0
0150 0  D1CA      396           STO    1 DCDB3-L
0151 0  C044      397    DUDEC  LD        =350
0152 0  91CA      398           S      1 DCDB3-L
0153 0  D1C9      399           STO    1 DCDB4-L
                  400    *
0154 0  C2E7      401           LD     2 DPHDC-C
0155 0  A2DB      402           M      2 DP-C
0156 0  1084      403           SLT       4
0157 0  D1C6      404           STO    1 DCDB7-L
0158 0  92DC      405           S      2 KPH-C
0159 0  A2E6      406           M      2 DPGDC-C
015A 0  1080      407           SLT       0
015B 0  D1E0      408           STO    1 LRADP-L
                  409    *
015C 0  C2E0      410           LD     2 BJDP-C
015D 0  92FC      411           S      2 DPPRL-C
015E 0  A2D2      412           M      2 TM15A-C
015F 0  1086      413           SLT       6
0160 0  D1C7      414           STO    1 DCDB6-L
                  415    *  SELECT HIGH
0161 0  B1E0      416           CMP    1 LRADP-L
0162 0  7002      417           MDX       *+2
0163 0  1000      418           NOP
0164 0  C1E0      419           LD     1 LRADP-L
0165 0  D1DE      420           STO    1 DRADP-L
                  421    *  SELECT HIGH
0166 0  B1C9      422           CMP    1 DCDB4-L
0167 0  7002      423           MDX       *+2
0168 0  1000      424           NOP
0169 0  C1C9      425           LD     1 DCDB4-L
016A 0  D1C8      426           STO    1 DCDB5-L
                  427    *
                  428    *  SELECT LOW
016B 0  B02A      429           CMP       =350
016C 0  C029      430           LD        =350
016D 0  1000      431           NOP
016E 0  D1C5      432           STO    1 DCDB8-L
016F 0  82EF      433           A      2 JDEC-C
                  434    *  SELECT HIGH
0170 0  B2EF      435           CMP    2 JDEC-C
0171 0  7002      436           MDX       *+2
0172 0  1000      437           NOP
0173 0  C2EF      438           LD     2 JDEC-C
0174 0  D1DD      439           STO    1 DEC-L
                  440    *  SELECT HIGH
0175 0  B1E1      441           CMP    1 JRA5-L
0176 0  7002      442           MDX       *+2
0177 0  1000      443           NOP
0178 0  C1E1      444           LD     1 JRA5-L
0179 0  D1DC      445           STO    1 JRA7-L
                  446    *
017A 0  C330      447           LD     3 P48P3-ISC
017B 0  1884      448           SRT       4
                  449    *  SELECT LOW
017C 0  B01A      450           CMP       =900
017D 0  C019      451           LD        =900
```

Table 2 -- Continued

```
017E 0  1000                 NOP
017F 0  D2DD                 STO    2 JPB-C
0180 0  A1DC                 M      1 JRA7-L
0181 0  108A                 SLT      10
0182 0  D1DB                 STO    1 JPF-L
0183 0  D073                 STO      FUEL
                    *
                    *                          COMPUTE IGV POSITION
0184 0  1000        LT80     NOP
0185 0  C012                 LD       =79
0186 0  D1DA                 STO    1 PATH-L
0187 0  C2E1                 LD     2 N-C
0188 0  92FA                 S      2 N1T-C
0189 0  D1D7                 STO    1 NN80-L
018A 01 4C300199             BP       LT90
018C 0  A006                 M        K1
018D 0  1082                 SLT      2
018E 0  82FB                 A      2 X1-C
018F 0  1881                 SRT      1
0190 0  D1D9                 STO    1 IGV-L
0191 0  D067                 STO      PIGV
0192 0  703F                 B        IGVDO
                    *
0193 0  0000        K1       DC       0
0194 0  0000        K2       DC       0
                             LORG
0195 0  FF38        +        DC       -200
0196 0  015E        +        DC       350
0197 0  0384        +        DC       900
0198 0  004F        +        DC       79
                    *
0199 0  1000        LT90     NOP
019A 0  C04B                 LD       =89
019B 0  D1DA                 STO    1 PATH-L
019C 0  C2E1                 LD     2 N-C
019D 0  92F8                 S      2 N2T-C
019E 0  D1D6                 STO    1 NN90-L
019F 01 4C3001B0             BP       LT100
01A1 0  C2F8                 LD     2 N2T-C
01A2 0  92FA                 S      2 N1T-C
01A3 0  D1D8                 STO    1 NXMNX-L
01A4 0  C2F9                 LD     2 X2-C
01A5 0  92FB                 S      2 X1-C
01A6 0  A1D7                 M      1 NN80-L
01A7 0  1080                 SLT      0
01A8 0  A9D8                 D      1 NXMNX-L
01A9 0  1080                 SLT      0
01AA 0  D1D4                 STO    1 IGVT1-L
01AB 0  82FB                 A      2 X1-C
01AC 0  1881                 SRT      1
01AD 0  D1D9                 STO    1 IGV-L
01AE 0  D04A                 STO      PIGV
01AF 0  7022                 B        IGVDO
01B0 0  1000        LT100    NOP
01B1 0  C035                 LD       =99
01B2 0  D1DA                 STO    1 PATH-L
01B3 0  C2E1                 LD     2 N-C
```

Table 2 -- Continued

```
01B4 0  92F6       509          S     2 N3T-C
01B5 0  D1D5       510          STO   1 NM100-L
01B6 01 4C3001C7   511          BP      GT100
01B8 0  C2F6       512          LD    2 N3T-C
01B9 0  92F8       513          S     2 N2T-C
01BA 0  D1D8       514          STO   1 NXMNX-L
01BB 0  C2F7       515          LD    2 X3-C
01BC 0  92F9       516          S     2 X2-C
01BD 0  A1D6       517          M     1 NM90-L
01BE 0  1080       518          SLT     0
01BF 0  A9D8       519          D     1 NXMNX-L
01C0 0  1080       520          SLT     0
01C1 0  D1D3       521          STO   1 IGVT2-L
01C2 0  82F9       522          A     2 X2-C
01C3 0  1881       523          SRT     1
01C4 0  D1D9       524          STO   1 IGV-L
01C5 0  D033       525          STO     PIGV
01C6 0  700B       526          B       IGVDD
01C7 0  1000       527    GT100 NOP
01C8 0  C01F       528          LD      =109
01C9 0  D1DA       529          STO   1 PATH-L
01CA 0  C2E1       530          LD    2 N-C
01CB 0  92F6       531          S     2 N3T-C
01CC 0  A0C7       532          M       K2
01CD 0  1085       533          SLT     5
01CE 0  82F7       534          A     2 X3-C
01CF 0  1881       535          SRT     1
01D0 0  D1D9       536          STO   1 IGV-L
01D1 0  D027       537          STO     PIGV
                   538    *                         END IGV COMPUTATIONS
                   539    *
01D2               540    IGVDD EQU     *
01D2 0  1090       541          SLT     16
01D3 0  2000       542          LDS     0
01D4 0  C2DB       543          LD    2 DP-C
01D5 0  1883       544          SRT     3
01D6 0  AADC       545          D     2 RPM-C
01D7 0  D023       546          STO     DFLPP
01D8 0  D1D2       547          STO   1 DPUP-L
01D9 30 040565C0   548          CALL    DAUP
01DB 1  01EC       549          DC      DALST
                   550    *
                   551    *
                   552    *
01DC 0  080D       553          XIO     CEOFF
01DD 0  1000       554    DONE  NOP
                   555    *
01DE 01 65800000   556          LDX  I1 IXR1
01E0 01 66800001   557          LDX  I2 IXR2
01E2 01 67800002   558          LDX  I3 IXR3
01E4 01 4C800006   559    LAST  BSC  I  CNTRL
                   560    *
                   561          LORG
01E6 0  0059       562    +     DC      89
01E7 0  0063       563    +     DC      99
01E8 0  006D       564    +     DC      109
01EA    0000       565    CEOFF BSS  E  0
```


Table 2 -- Concluded

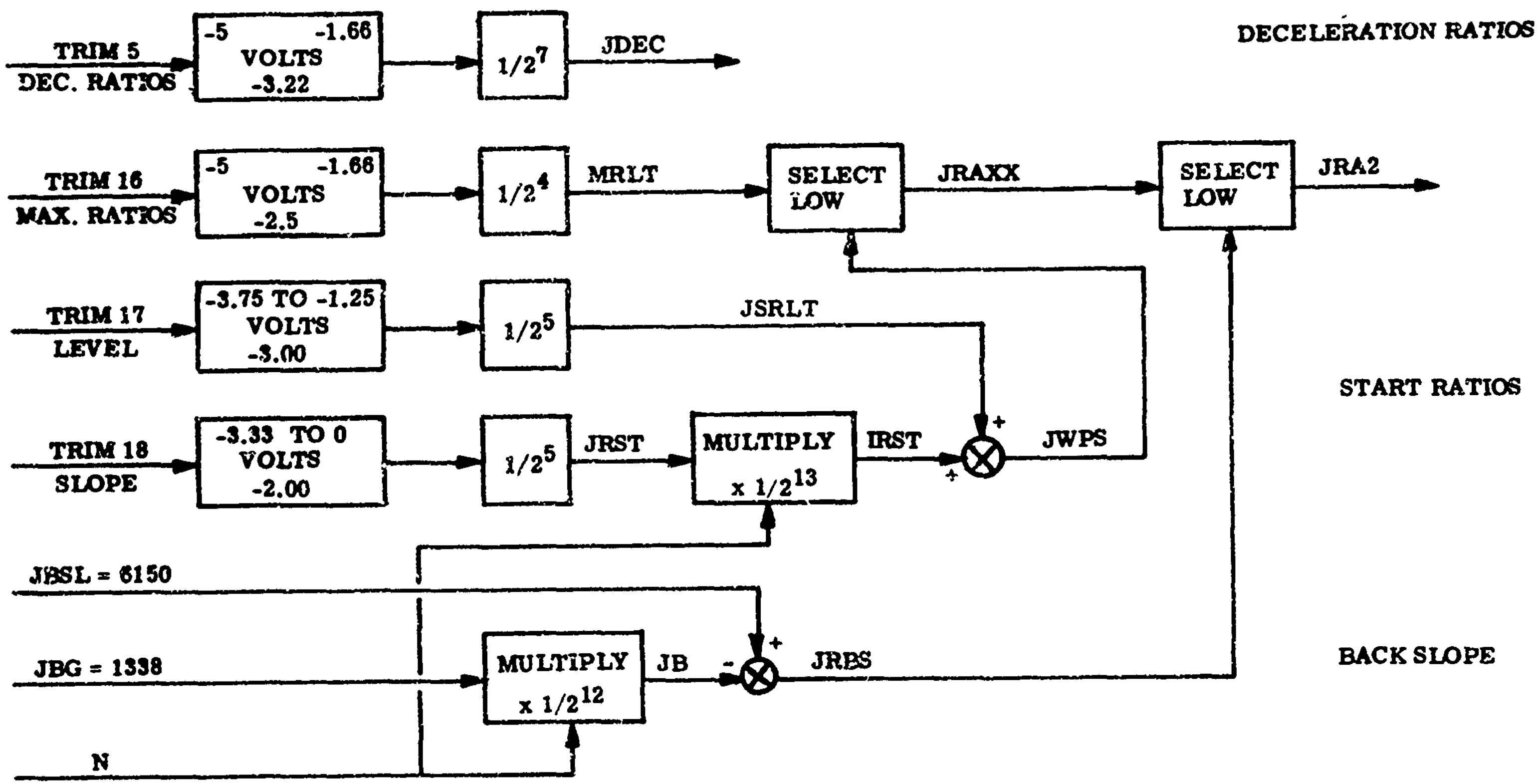


Figure 9 -- Fuel-Pressure Ratios Bounds

In the mid-speed range a fixed maximum ratios is used equal to 410 multiplied by the voltage of Trim 16. At the nominal setting of 2.5 the maximum counts is 1025 equal to 31.3 ratios. The nominal start schedule equals this value at 10,650 rpm.

There is also a back slope schedule in which counts = 6150 - 1338 $N/2^{12}$. At maximum speed of 16500 rpm, the back slope yields 790 counts or 24.1 ratios. The required to run counts of 650 would occur at 17,200 rpm equal to 104 percent.

ENGINE VARIABLE GOVERNORING

Three engine variations are included in a closed loop. The differences between request for and engine speed, turbine temperature or burner pressure are added to the base ratios as set by Trim 9. Engine speed is used as the selected input parameter for the control system. Pressure and temperature loops are included as safety loops which can be used. Either or both signals can be set to provide an upper speed limit in event of speed control failure. Also the temperature circuit can be used for start control protection operation. A block diagram illustrating these control loops is shown by Figure 10.

The speed control loop is varied by Trims 1, 2, and 6 and by the throttle input. Trim 1 is used to set the minimum speed for an investigation sequence. The selected speed is:

$$N = \text{rpm} = \text{counts} = 10{,}000 + 819 \text{ (Volts Trim 1)}.$$

Selected speed in percent and rpm is given by the following list:

N RPM	10000	10710	11550	12380	12730
N%	60.5	65	70	75	77
Volts	0	.86	1.89	2.9	3.33

Trim 2 is used to set the maximum speed for an investigation. The selected speed is:

$$N = \text{rpm} = \text{counts} = 13000 + 819 \text{ (Volts Trim 2)}.$$

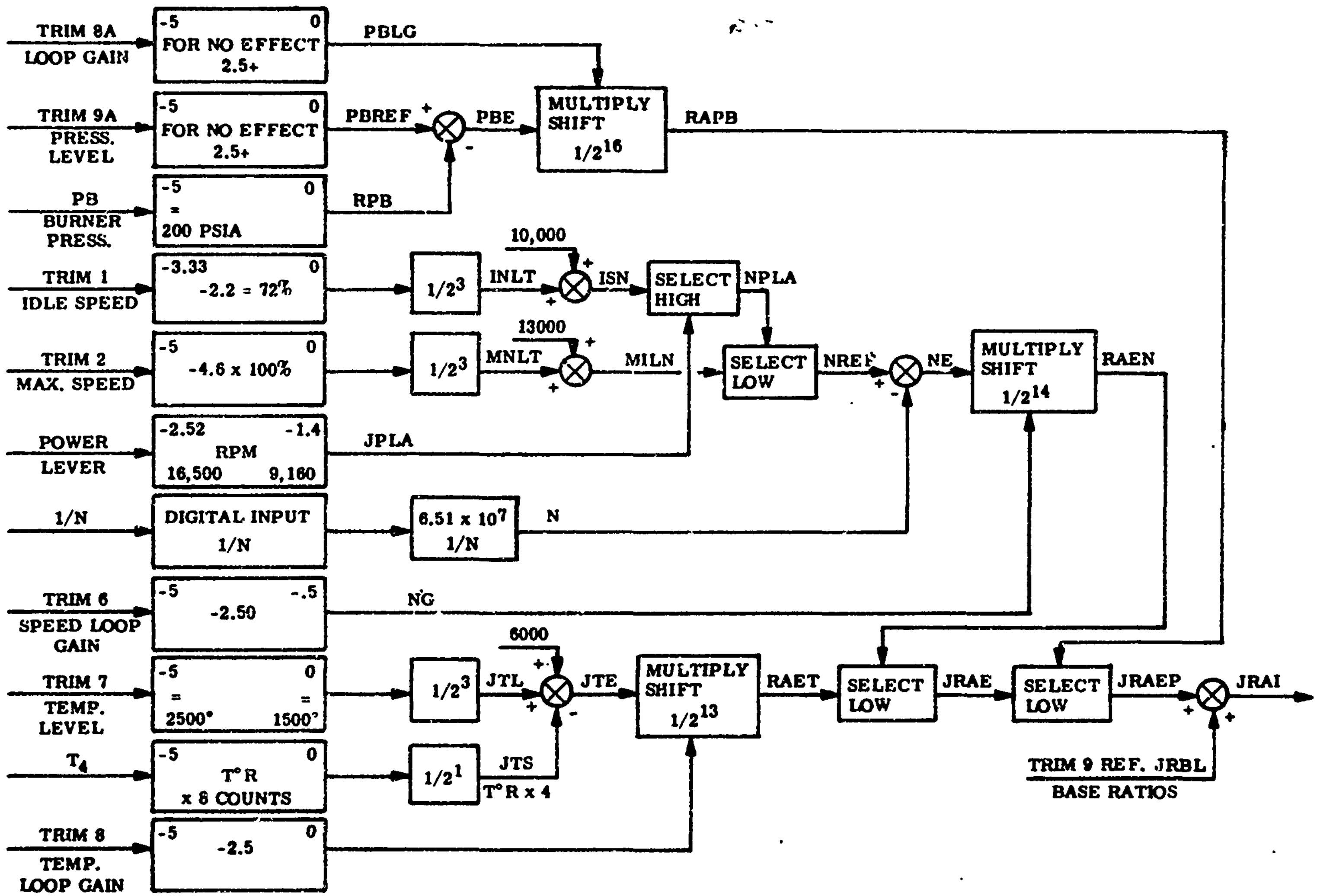


Figure 10 -- Speed Temperature and Pressure Control Loops

Selected maximum speed in percent and rpm is given by the following list:

N RPM	13000	13200	14020	14850	15690	16500	17096
N%	78.8	80	85	90	95	100	103.4
Volts	0	.24	1.25	2.26	3.27	4.27	5

Throttle speed request is in the form of a voltage where,

$$N = \text{rpm} = \text{counts} = 6553 \text{ (volts throttle)}.$$

Throttle counts are compared with minimum speed counts and the highest selected. Also the throttle counts are compared with the maximum speed counts and the lowest is selected. The throttle can thus be moved through a large range but the speed is selected by the trims.

Selec'ed speed is compared to the actual speed and the difference is multiplied by the gain set by Trim 6. The error in speed multiplied by the gain then becomes a counts effective as ratios counts. This can be expressed as:

$$\text{ratios counts} = \Delta N\ (.4)(\text{Volts Trim 6}).$$

If the gain is 2.5 volts the speed error is equal to count ratios or 32.8 rpm error is one fuel-pressure ratios.

The temperature control loop is varied by two trims. Trim 7 sets the temperature request level, where request = 6000 + 819 (volts Trim 7). The request in counts is equal to four times the request in degrees R. Temperature is input through the A/D converter and scaled such that 5 volts will equal 16383 counts which will equal four times the temperature in degrees R. In table form the temperature request is:

Temperature	1500	1705	1910	2115	2319	2524
Volts Req	0	1	2	3	4	5
Volts sensor	1.83	2.08	2.33	2.58	2.83	3.08

Sensor volts = 1.22×10^{-3} Volts/°R for the loop as specified.

Comparison of the request and temperature yields a temperature error. This error is multiplied by a gain set by Trim 8 to obtain:

$$\text{Counts} = 3.2\ (\text{Volts Trim 8})\ \Delta T°R =$$

ratios in counts, or about 10° and a gain of one volt will yield one fuel-pressure ratio.

A burner pressure control loop is provided. The burner pressure sensor circuit yields an output of 5 volts equal to 200 psia. A burner pressure reference level is set by Trim 8A. Neither of these senses is scaled and a request voltage is equal to sensor voltage at zero error. The sensor and reference counts are 164 counts equal one psi. These two values are compared and multiplied by a gain Trim 9A to yield:

$$\text{Counts} = 16.4\ (\text{Volts Trim 9A})\ \Delta P$$

or at one volt of Trim 9A two psi error yield one fuel-pressure ratio.

A comparison of the temperature, pressure and speed control loops are made in a select low logic circuit. The lowest value is added to the base ratios set by Trim 9. Base ratios are set near the required to run so that no or a small error exists in the control at steady state.

PRESSURE RATIOS ACCELERATION CONTROL

Acceleration control by pressure ratio is shown in two forms by Figure 11. One method utilizes the error between the sensed value and requested value of the pressure ratio to establish an integration rate of ratios request counts. The other method utilizes the difference proportionally to decrease the maximum ratios being requested. In order to accomplish this control, a scheduled step and ramp are used for limits of request ratio counts as a function of time.

Computations are started at the base ratios value. Base ratios are set near required to run value by Trim 9 which yields,

$$\text{Counts} = 410\ (\text{Volts Trim 9}).$$

A step is added by Trim 3 to the base ratios to obtain the minimum acceleration value. The step counts = 205 (Volts Trim 3). A ramp is also added to the sum of the base ratios and the step. The ramp is a value which is added to the previous value each computation cycle, that is, each 0.01 second. An error in speed which is equal to 256 counts must be present to cause the ramp to become effective. The ramp set by Trim 4 is, counts = 12.8 (Volts Trim 4). Thus when an increase in speed is requested, the step sets the initial acceleration value, and if the speed request is greater than 256 counts, the ramp becomes effective to add to the step.

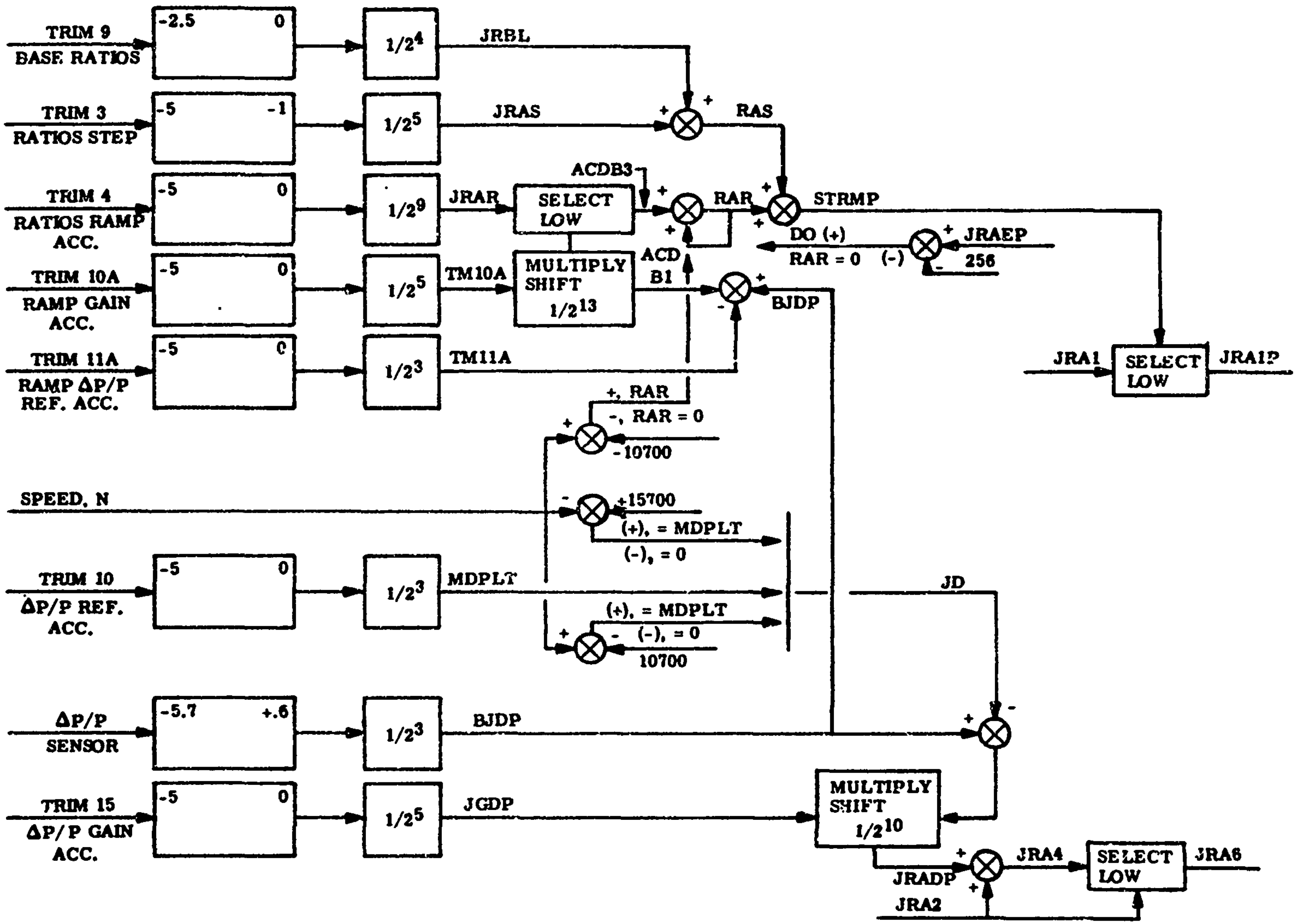


Figure 11 -- Pressure Patios Acceleration Control

The ramp value is in a select low loop with the difference between $\Delta P/P$ (pressure ratio) sensor and the desired value of $\Delta P/P$ set by Trim 11A. This difference is multiplied by the setting of Trim 10A. Thus the ramp due to $\Delta P/P$ loop is:

$$\text{Counts} = 20 \text{ Volts } \Delta(\Delta P/P) \text{ (Volts Trim 10A).}$$

A second loop of $\Delta P/P$ control is also included. In this loop the difference between a requested value of $\Delta P/P$ set by Trim 10 and the sensor value is multiplied by the gain of Trim 15 to influence the maximum ratio set by Trim 16 through a select low loop. Sensor voltage is near -2.5 at steady state and decreases in magnitude (toward a positive value) during an acceleration. The sensor voltage must be less negative than the request voltage to influence the acceleration. The effect of the loop is:

$$\text{Counts} = 164 \text{ Volts } \Delta(\Delta P/P) \text{ (Volts Trim 15).}$$

Logic in the control program is used to maintain the ramp value at zero until a speed of 10,700 rpm is reached. Also logic maintains the request of the $\Delta P/P$ value at zero below 10,700 and above 15,700 rpm.

PRESSURE RATIOS DECELERATION CONTROL

Deceleration control by pressure ratio is shown in two forms by Figure 12. One method utilizes the difference between the sensed value and request value to establish an integration rate of ratios request counts. The other method utilizes the difference proportionally to add to the minimum ratio counts.

A deceleration computation is started when a speed request less than the engine speed is requested. A step is input between the required to run value of counts and the speed error in counts limited by the deceleration ratios set by Trim 5 plus 350 counts. The maximum count value of Trim 5 is 256. Thus the maximum deceleration counts is 606 which yields about 50 counts step when the throttle is retarded. If the speed error exceeds a negative 200 counts, a ramp determined by Trims 12A, 13A and 14A has an effect.

Trim 14A is used to set the reference value of $\Delta P/P$ during the deceleration. Since the sensor voltage is near -2.5 volts at steady state and becomes more negative during a deceleration, the Trim 14A voltage is set at a more negative value than -2.5 The difference is multiplied by the value of Trim 13A to yield:

$$\text{Counts} = 20.5 \text{ Volts } \Delta(\Delta P/P) \text{ (Volts Trim 13A).}$$

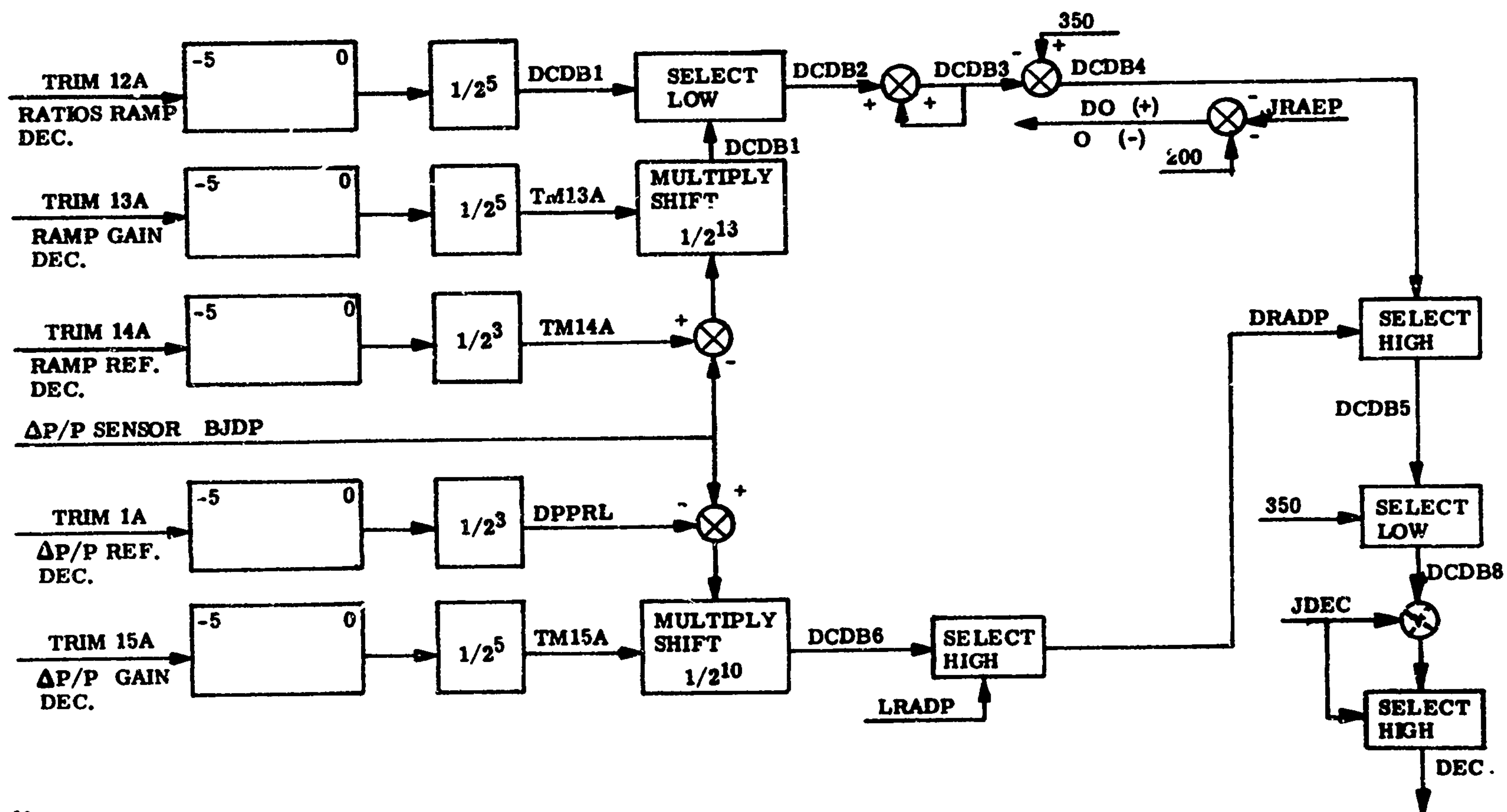


Figure 12 -- Pressure Ratios Deceleration Control

The low value of the two ramp ratios causes a decrease in the set value of 350 by the value of the ramp for each computation cycle. This in turn allows the value of deceleration counts to decrease until the control value is reached.

The second loop is proportional to the error between the sensor voltage and the request set by Trim 1A. This difference is multiplied by the gain of Trim 15A to yield:

$$\text{Counts} = 164 \text{ Volts } \Delta(\Delta P/P) \text{ (Volts Trim 15A)}.$$

The counts are added to the deceleration ratios set by Trim 5. In order for the loop to be effective the ramps must be set high enough that the value of symbol P^DB4 is less than DRADP. Trim 1A voltage is set more negative than steady-state sensor voltage and the sensor voltage decreases below that value yielding positive counts which add to the JDEC deceleration counts.

<u>SECONDARY PRESSURE RATIO LOOPS</u>

Another approach to the acceleration and deceleration control by pressure sensing is shown by Figure 13. Since the acceleration value of $\Delta P/P$ is nearly constant, that is,

$$\Delta P/P = K, \text{ and}$$

$$\Delta P/K = P.$$

It would appear that control could be affected by multiplying ΔP by some constant (the K above is less than unity) and comparing the results with PB. The decrease in maximum counts during an acceleration is given by:

$$\text{Counts} = \{[2621 \text{(Volts Trim 11)} (\Delta P \text{ Volts})] -6553 \text{ (PB Volts)}\} (-1 \text{ Volts Trim 12}).$$

The result of this computation is used to decrease the maximum counts proportional to error.

Deceleration control is given by the equation:

$$\text{Counts} = \{[2621 \text{(Volts Trim 13)} \Delta P \text{ Volts}] -6553 \text{ (PB Volts)}\} (.1 \text{ Volts Trim 14}).$$

The result of this computation is compared by select high logic to the results of deceleration control computations above to establish the deceleration counts.

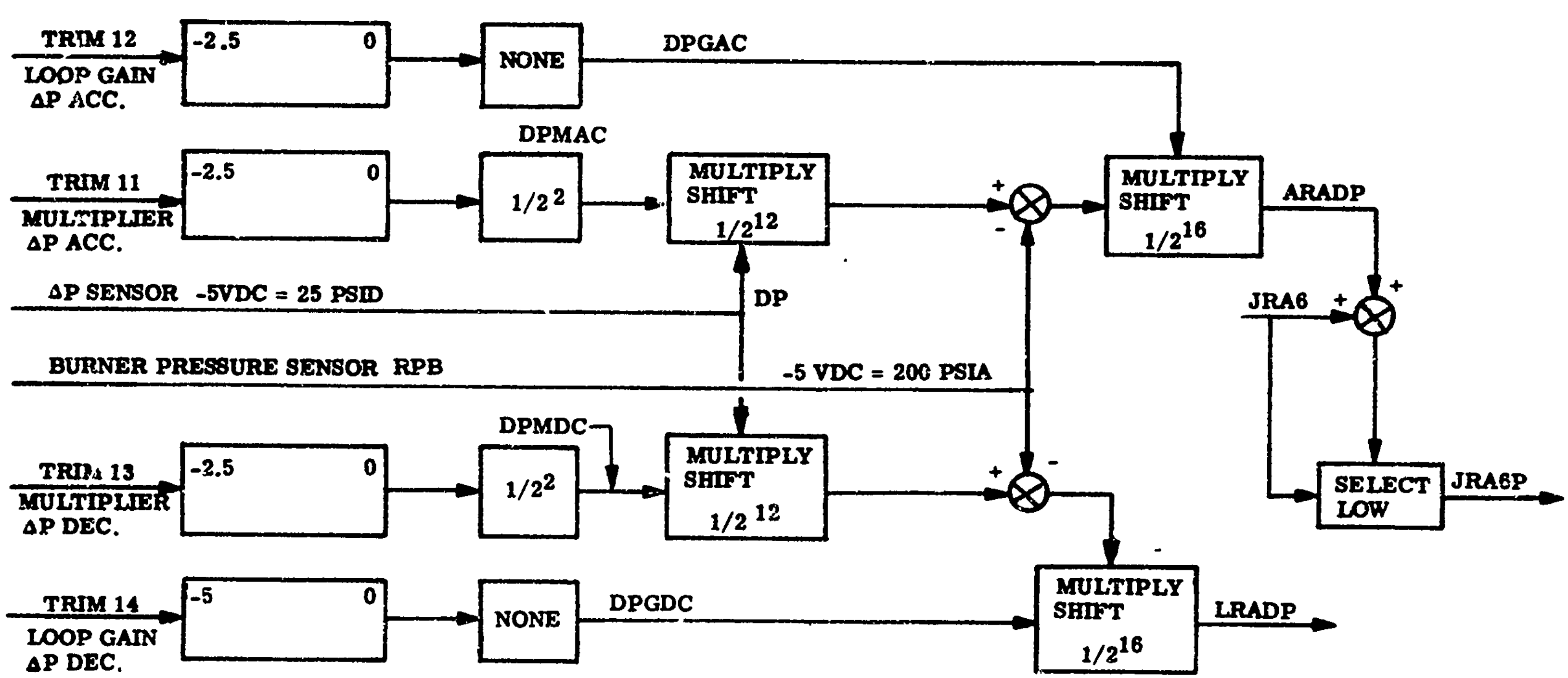


Figure 13 -- Secondary Pressure Ratios Acceleration and Deceleration Control

GEOMETRY SCHEDULE COMPUTATIONS

Figure 14 illustrates the bleed and guide vane position computation. Bleed position obtained by engine running on the parts list control was nearly linear. A schedule of four straight lines was established. Below 83% speed, the bleeds were maintained open. At speeds greater than 100% the bleeds were maintained at the value established on the day of running to establish a schedule. The schedule shown by the figure is one straight line between 83% and 100% speed. The midpoint calculation would not have been necessary.

The program illustrated by the block diagram compares speed and selects the speed range of operation and than the position value is calculated for the applicable speed range. The speed is first compared with the value set by Trim 7A which is 16,500 rpm equal 100% for the program used. In the current use of the program, this step is not necessary. If however there were a speed above 100% or some other programmed speed, the comparison would be positive and the position set by Trim 6A designed X3 would have been increased by the speed difference times the slope designated by K2.

When the speed is less than that set by Trim 7A, the comparison is negative and the next comparison of speed set by Trim 5A is made. If positive, the calculation of path 99 is made. The value of the position is than the linear interpolation between positions of Trim 4A and Trim 6A. If comparison of N and N2T is negative, than the comparison of N and NIT is made and the indicated path of computation is followed.

The selected value of the position is divided by two in order to achieve the output voltage from the D/A converter equal in magnitude to the input request voltage. This is for convenience of checking operation of the loop. At bleed open position (low speed) path 79 the request (Trim 2A) was set to -1.58 volts, the DAC output was +1.58 and the position read from the position potentiometer was -1.58 volts.

Computer program computations are shown by Table 2.

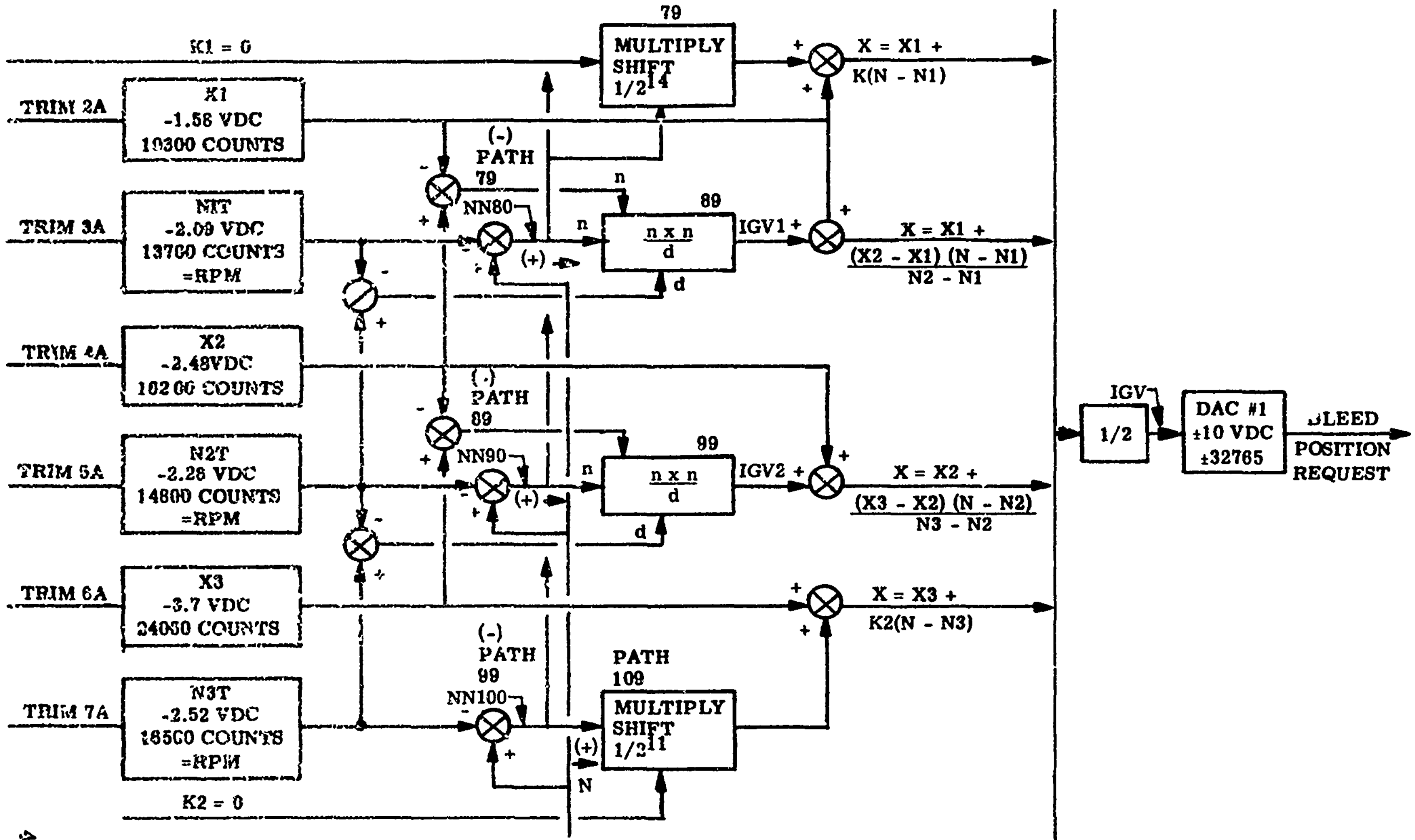


Figure 14 -- Computation for Bleeds and Guide Vane Schedule

SECTION IV

SYSTEM INSTALLATION AND CHECKOUT

Figure 15 shows the plan view of the control room as presented in Reference 2. Location of the Pace TR-48 analog computer and the control electronics interface are indicated on the figure. A GE J85-7 engine was installed in the test chamber. Figure 16 shows the bleed portion of the engine. Location of the position feedback potentiometer is indicated and the hydraulic lines which were rerouted through the selection valve plumbing are shown.

INSTALLATION

In Section II the general arrangement of the assemblies comprising the engine - control system was presented. In this section some detail of the interconnecting cabling and component installation are listed.

Test Chamber Components

Figure 17 shows the end of the cable bundle and components used for the program reported in Reference 1. For the current program a second CEC 4-326-0001 pressure transducer and a second burner pressure pickup adapter were added. The second transducer is tied into the high pressure line to the pressure ratio sensor. The second adapter is used to provide pressures to a CEC-4-312-0002 differential pressure transducer. The burner pressure sensor used for fuel calculation by the computer program is attached to the third port of the second adaptor.

The servo valve is tied into the bleed actuator hydraulic lines indicated by Figure 16. The valving for this plumbing is indicated by Figure 3.

Cables are attached to the components and to the interface connectors as indicated by cable and connector markings.

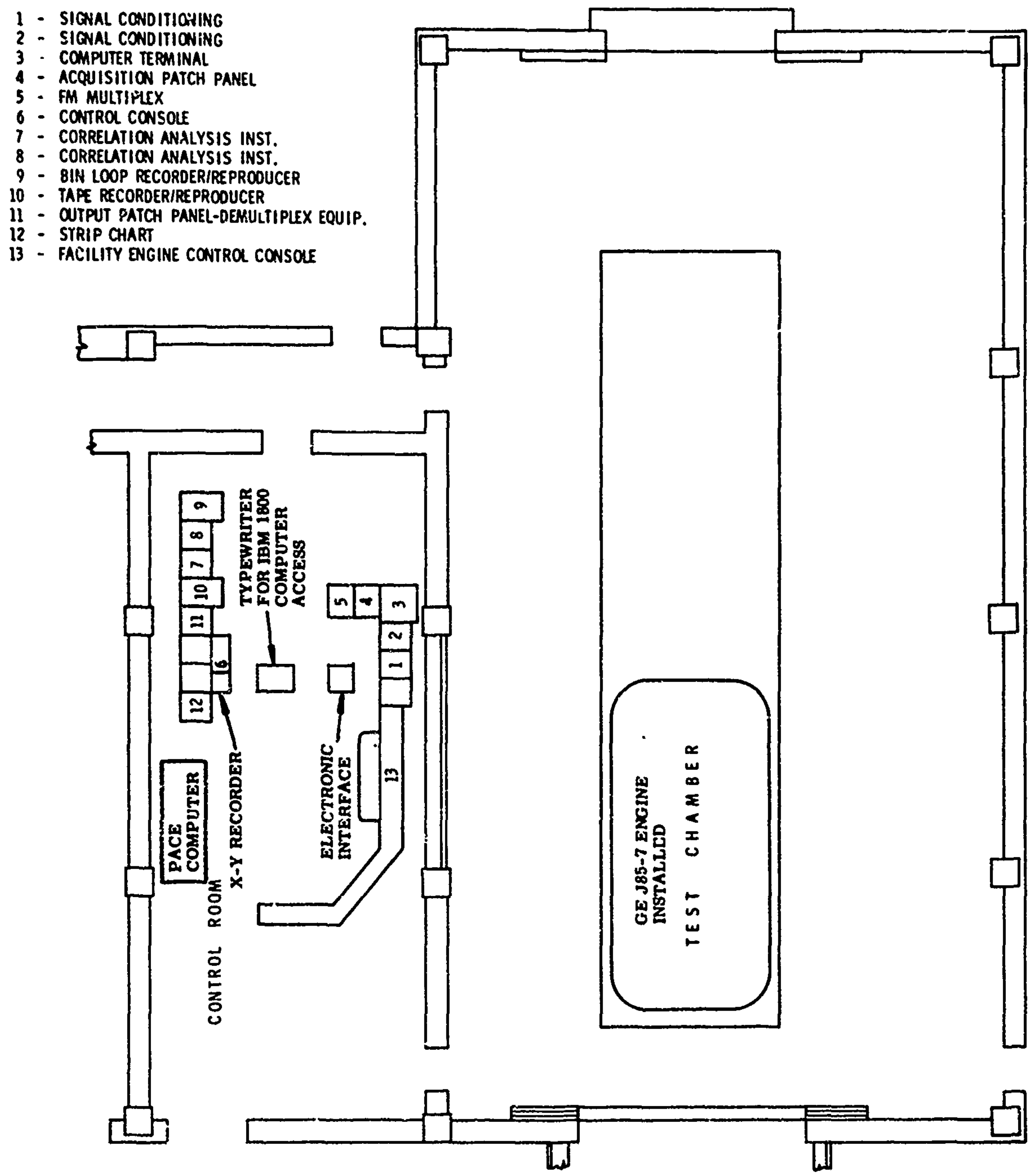


Figure 15 -- Plan View of Control Room

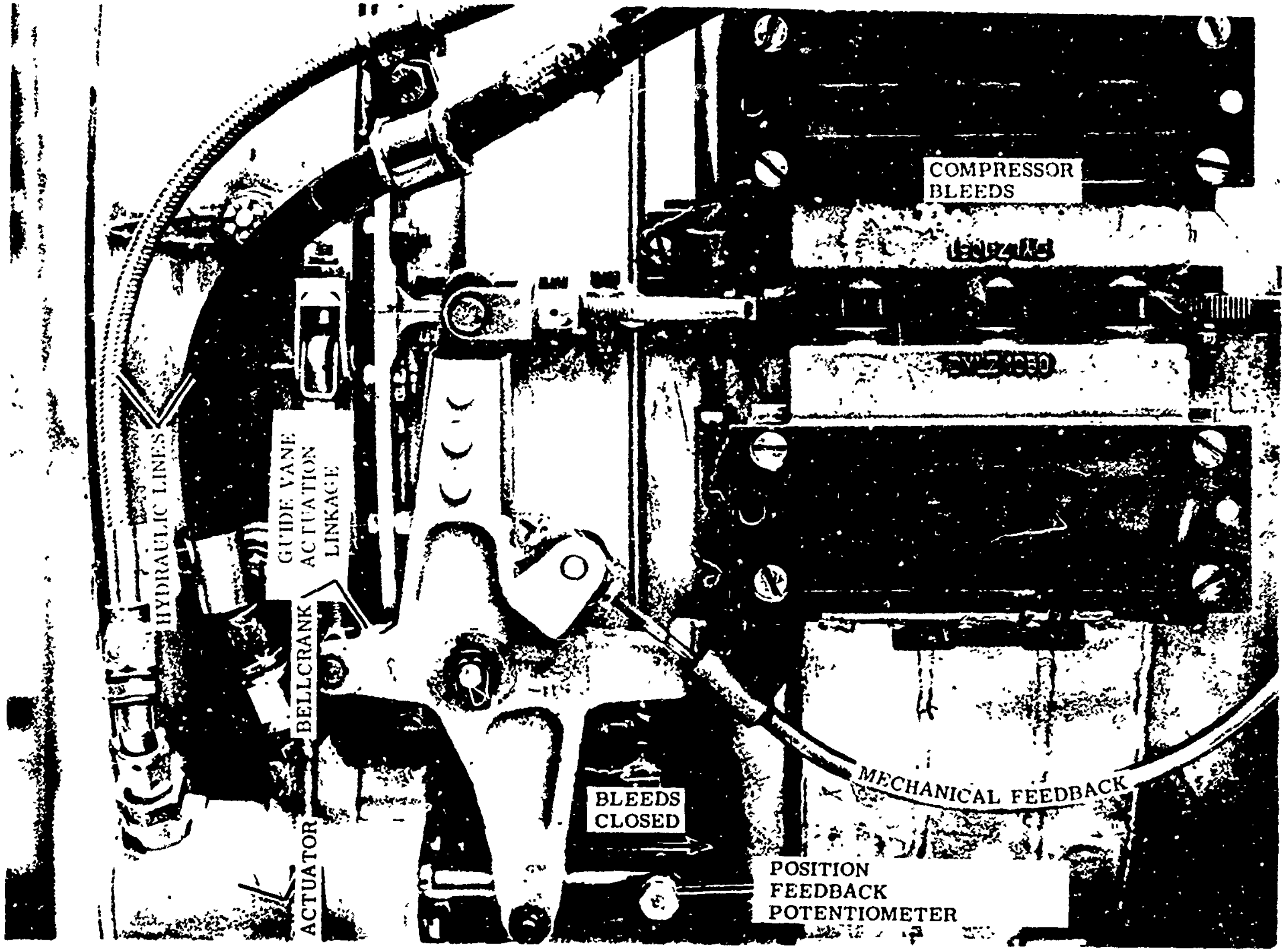


Figure 16 -- View of External Bleed Door Actuation Linkage

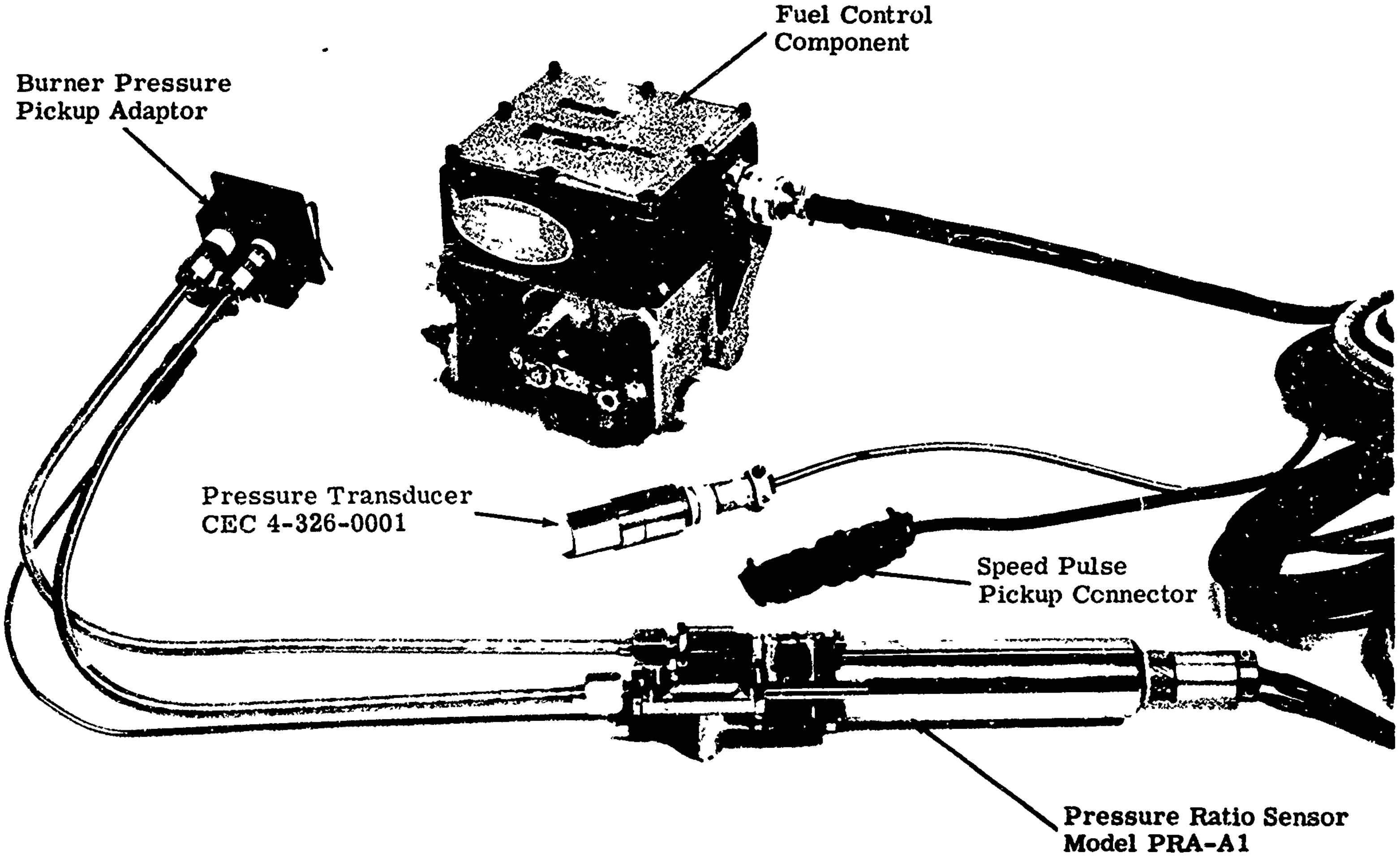


Figure 17 -- Engine Wiring Cable and Components

Pace Computer

The pace computer is programmed and attached to the interface as indicated on the cable provided. Pace outputs to the interface consist of:

- Power lever, PLA
- Pressure ratio, $\Delta P/P$
- Burner pressure, P3

  This signal is used for burner pressure PB also by two inputs to the interface.
- Differential pressure, ΔP.

  The above five signals are input directly to the interface isolation amplifiers outputs to the computer terminal, whereas, the engine signals are input through resistors to the same point. Thus, the engine components can be connected during simulation checkout but the analog computer input lines must be disconnected before the engine components can be used.
- Turbine Temperature, T4

  This signal is input through the EK14 instrumentation line.
- Engine Speed, N

  This signal is input in parallel with the electro-magnetic signal. The signal is generated in a voltage to frequency converter. This line must also be disconnected before engine running.

IBM 1800 Computer Terminal Connections

Six cables are used to connect the interface to the computer terminal. The connections are to terminal points listed below:

- EK14 Analog Signal Cable
  - Trims 1 through 18 are connected to terminal points 27 through 44.

- Pressure ratio, $\Delta P/P$, to point 45
- Power lever, PLA, to point 46
- Turbine temperature, T4, to point 47
- Burner pressure, P3, to point 48.

- EK15 Analog Variable Signals
  - Burner pressure, PB, to point 49
  - Differential pressure, ΔP, to point 50. Points 51, 52 and 53 are spare points not used in the program.
  - Pressure circuits 3 and 4 and position feedback POS1, POS2, POS3, and POS4 were not connected.
- EK15 Trim Cable #1
  - Trims 1A through 9A are connected to terminal points 18 through 26.
- EK15 Trim Cable #2
  - Trims 10A through 16A are connected to terminal points 54 through 61.
  - Instrumentation signals #1 and #2 incorporated in this cable were not used.
- EK14 Engine Speed Signal, N
  - This fifteen bit word was connected to digital input word number 1. The sync signal was input to the sign bit point.
- EK15 Frequency Signal
  - This fifteen bit word was not used in the program but was connected to digital input word number 2. The sync signal was connected to the sign bit point.

- Digital to analog converter signals
    - Fuel valve position request, DAC O
    - Bleed and guide vane position request, DAC 1
    - Quotient of differential pressure divided by burner pressure $\Delta P/PB$, DAC 2.

<u>Instrumentation Cables and Instrumentation Inputs</u>

Three instrumentation cables are provided with the interface and three signals are obtained from the facility data acquisition devices.

- EK14 Instrumentation Cable
    - Fuel valve position for fuel flow indication to the X-Y and strip recorders.
    - Analog speed signal (10 volts equals 100% N) for speed signal to the X-Y recorder and to the strip recorder.
    - Turbine temperature input from Pace Computer.
    - Pressure ratio, $\Delta P/P$, to strip recorder.
- EK15 Instrumentation Cable #1
    - Bleed valve position on the strip recorder.
    - Pressure ratio, $\Delta P/PB$, from IBM 1800 DAC 2 to the strip recorder.
- EK15 Instrumentation Cable #2
    - Burner pressure, PB, to the strip recorder.
    - Differential pressure, ΔP, to the strip recorder.
- 7/16 inch Potter flow meter to the strip recorder.

- 3/8 inch Potter flow meter to the strip recorder.

- Turbine temperature to the strip recorder.

CIRCUIT CHECKOUT PROCEDURE

The circuits are checked for operation both with engine off and with the engine operating. All trims are moved and set to nominal values by observation of signals on the voltmeter. Outputs of engine signals are read on the voltmeter. These circuits are adjusted for proper non-running outputs if needed. The IBM 1800 program is placed on line and a print out of all computer inputs points obtained. These are checked for agreement with the settings made.

The engine is started on the parts list control and a strip recording of the start is made. A strip traces of and a computer printout of the variables for several speed values are obtained. These data are examined to ascertain the validity of transducer operation and to establish bleed valve schedule and start fuel schedule.

During these checkouts, signals were observed on an oscilloscope to determine line noise. The digital to analog signals of fuel valve position request and pressure ratio were found to be excessively noisy. These signals were changed 100 times per second, hence the output appeared as steps. Since the computer reads point input values, any frequency noise can cause the steps in the DAC signals depending on read cycle in relation to noise frequency. Two prominent sources of noise were found. First, there were some ungrounded shields which introduced 60 cps noise on the pressure signals. Second, there was high frequency noise from the IBM 1800 special power supply. Elimination of these two relatively high amplitude noise inputs brought all signal noise within tolerable bounds.

During the previous program there had been a discrepancy between set values and computer read values. The isolation amplifiers added to the interface output circuits as line drivers eliminated this problem.

SIMULATED ENGINE CONTROL

The Pace computer cables are connected to the interface and the control program is put into operation. Various loops of the control program are checked and operation of various adjustments is ascertained.

Speed request is from the computer in a form which can be switched from idle to maximum to idle by snap action. Each of the adjustments and groups of adjustments is checked in turn during acceleration and deceleration requests to establish valid solution of the mode by the IBM 1800 computer program. Two reversed signs in addition circuits were found during these checkouts.

AUXILIARY PUMP CHECKOUT

After start and bleed schedules are programmed, the auxiliary pump is used to provide flow. A speed signal is obtained from an oscillator and operation of the two control loops are checked.

Setting the bleed schedule is very simple, speed point trims are set at 1/40 the percent speed and the geometry value trims are set at feedback voltage obtained when the control was on the hydromechanical system. Bleed schedule is a function of inlet temperature as well as speed. The schedule was established on a hot day resulting in the bleeds being more open on cooler days than the hydromechanical schedule would have been. The bleed position request was switched from DAC1 to the manual input to check the manual position request.

Starting fuel schedule had been established during the previous program. The schedule was checked to determine operation of the fuel control and computer program in the start region. The fuel flow was low because of the low value of the burner pressure.

The bleed position and fuel flow circuit each have provisions for parallel inputs. An oscillator input was used to check these circuits.

ENGINE START UP TO CHECK FUEL START SCHEDULE

The engine was started on the parts list control while the electronic control was operating on the auxiliary pump. During this test, the burner pressure was at engine operating conditions and the start schedule and acceleration and deceleration flow at various speeds were checked by manipulation of the electronic control throttle to obtain a request above and below the engine speed.

SECTION V

ENGINE TEST RESULTS

Most engine tests were limited to the range between 70 and 95 percent speed. The engine has accumulated 200 hours of operation and the case has been cut in numerous places for mounting of instrumentation. Since the AFAPL have several test sequences planned for the engine, most testing was conducted under rather mild conditions of operation. In the test sequences conducted for this program, nearly 250 acceleration and deceleration cycles were accomplished and the engine was stalled three times.

During the test period, the fuel spray nozzles had to be cleaned, the bleed doors had to be replaced, and one bleed actuator bellcrank was broken and replaced. Intentional engine stalls were limited to those necessary to accomplish program objectives since damage to the engine can occur. Enough stalls were made to establish that moving the bleeds closed to stall the engine produced no indication of stall before the stall occurred.

The engine was accelerated and decelerated at ground level conditions and simulated altitude conditions to demonstrate feasibility of the control mode. The sensor used (the Bendix PRA-A1 pressure ratio sensor) did not have sufficient range because of physical travel limits in this unit to demonstrate both rapid accelerations and decelerations with a single setting. There was a shift in steady state sensor output value between ground level and altitude. In this rather short program no attempt was made to develop the sensor for full acceleration plus deceleration range of operation nor was an attempt made to locate a probe position which may have been equally valid for altitude and ground level operation.

The altitude tests included in this sequence showed the change in value of $\Delta P/P$ with altitude as the sensor probes were located in the engine. Additional investigation would be required to determine if this change is characteristic or if an experimentally selected sensing probe(s) location would give uniform results at all altitudes.

ENGINE TEST LOG SHEET

TYPE TEST DATE TIME

Variable	Start Setting	SETTINGS Name	No Effect	Loop to Control
Trim 1	2.00	Idle speed		At desired idle setting
2	3.57	Max. speed		At desired max. N setting.
3	4.9	Ratios step	4.9	Greater than zero
4	4.9	Ratios ramp	4.9	Greater than zero
5	2.0	Dec. ratios		1.7 to 5.0 volts
6	1.0	Speed Gain		0.5 to 5.0 volts
7	4.9	Temp. Level	4.9	Too obtain counts
8	2.0	Temp. Gain	2.0	Greater than zero
9	1.6	Base ratios		Near 1.6
10	0	$\Delta P/P$ Level		At desired sensor voltage
11	2.0	ΔP Multiplier		ΔP Counts > P_B Counts
12	0	ΔP ACC gain	0	Greater than zero
13	2.0	ΔP Dec. Multi.		ΔP Counts > P_B Counts
14	0	ΔP Dec. gain	0	Greater than zero
15	0	$\Delta P/P$ gain	0	
16	2.5	Max. ratios	High	1.7 to 3+ volts
17	3.0	Start Level	High	As required
18	2.0	Start slope	High	As required
1a	4.0	$\Delta P/P$ Dec. Ref.	4.9	At desired sensor
2a	1.60	X1		
3a	2.12	N1T		
4a	2.47	X2		
5a	2.26	N2T		
6a	3.73	X3		
7a	2.52	N3T		
8a	2.0	Press. gain	2.0	Greater than zero
9a	3.5	Press. level	3.5	At desired P3 volts
10a	0.0	Ramp Gain Acc.	2.0	Greater than zero
11a	0	Ramp Ref. $\Delta P/P_{Ac}$	0	At desired sensor voltage
12a	.5	Ratios ramp dec.	4.9	Greater than zero
13a	2.5	Ramp gain Dec.	2.5	Greater than zero
14a	4.9	Ramp ref. Dec.	4.9	At desired sensor voltage
15a	0	$\Delta P/P$ gain Dec.	0	Greater than zero
Trim 16a	0			
Speed Min.				
Speed Max.				
Inlet Pressure				
Inlet Temperature				

Table 3 -- Trim Setting for Various Control Modes

TEST PROCEDURES

Control system adjustments were set to the values shown by Table 3 for engine starting. After the start, adjustments which could interfere with tests on the loop being investigated were set out of the way of loop operation. Values for the various trims for effect and no effect on the various loops are also shown on Table 3.

The engine was accelerated with the throttle to maximum request rpm. The setting of Trim 2 limited the maximum speed obtained. After the high speed was obtained, the request for low speed was accomplished by closing a switch which loaded the throttle potentiometer causing a low speed request. Accelerations and decelerations were then made by opening and closing the switch.

Values of adjustments to be effective during various control modes were selected. The engine test log sheet Table 4 contains the numbers of figures demonstrating the effects of the adjustment. Log sheets were used to record trim setting used for various engine transients. The applicable setting values are listed on each figure.

VARIABLE CONTROL

Several features and loops of the control system were used in test program execution but only that data specifically pertinent to program objective is presented in this report.

Speed Control

Speed control is a proportional loop. Tests showed that adjustments could result in stable, underdamped, or oscillatory conditions. Actual set points were established as discussed in the following paragraph.

The gain of the speed control was maintained at a setting of one volt. At this setting one percent speed error causes an effective fuel change of ten percent and seven percent of steady state fuel at 100 percent and 70 percent speed, respectively. This gain, Trim 6, was adjusted to five volts for loop checkout. At 70 percent the system was stable to the five volts, and at 100 percent the system was oscillatory above a setting of 4.5 volts. Speed over shoots were greater and the speed oscillated for a couple of seconds at the end of transients with gain settings significantly higher than the one volt used.

ENGINE TEST LOG SHEET

TYPE TEST DATE

Variable	Start Setting	Name	Applicable Figures			
Trim 1	2.00	Idle speed	19			
2	3.57	Max. speed				
3	4.9	Ratios step	18			
4	4.9	Ratios ramp	19			
5	2.0	Dec. ratios	18	24		
6	1.0	Speed Gain				
7	4.9	Temp. Level				
8	2.0	Temp. Gain				
9	1.6	Base ratios				
10	0	$\Delta P/P$ Level	22	30		
11	2.0	ΔP Multiplier				
12	0	ΔP ACC gain				
13	2.0	ΔP Dec. Multi.				
14	0	ΔP Dec. gain				
15	0	$\Delta P/P$ gain	22	30		
16	2.5	Max. ratios	18			
17	3.0	Start Level				
18	2.0	Start slope				
1a	4.0	$\Delta P/P$ Dec. Ref.	24	26	32	
2a	1.60	X1				
3a	2.12	N1T				
4a	2.47	X2				
5a	2.26	N2T				
6a	3.73	X3				
7a	2.52	N3T				
8a	2.0	Press. gain				
9a	3.5	Press. level				
10a	[illegible].0	Ramp Gain Acc.	20		28	
11a	0	Ramp Ref. $\Delta P/P$ Ac	20	22	28	
12a	.5	Ratios ramp dec.	18	24	26	27
13a	2.5	Ramp gain Dec.		24	31	
14a	4.9	Ramp ref. Dec.			31	
15a	0	$\Delta P/P$ gain Dec.	24		26	32
Trim 16a	0					

Table 4 -- List of Figures Illustrating Trim Effects

Pressure Control

The burner pressure control was used as a safety control loop. During start the pressure trim 9A was set at one volt equal to maximum selected value of forty psia. After the start the setting was changed to 2.2 volts which is a setting of 88 psia. In the control program the pressure is compared to a set maximum number (300 equal to 88 psia) as a safety loop. This protects against a failure which would cause high voltage in the sensor circuit.

With the start pressure controlling at approximately 78 percent speed, the throttle was advanced to maximum speed request. The pressure level request was than gradually increased allowing control at various speeds. The loop was stable at the 2.5 volts gain setting (Trim 8A) used during the tests.

During altitude tests the start pressure setting was set at .75 volt equal to 37.5 psia. The trim was left at this value for some of altitude transients and the traces of figures 28 and 30 shows pressure control established by this limit above 90 percent speed.

Temperature Control

The temperature was being recorded on the strip chart and the temperature control loop was checked by the Pace simulation. Temperature was not used as an engine control during this test sequence. The AFAPL has a temperature control test sequence planned.

Secondary Pressure Ratio Control

This loop was included in the program to obtain parallel information on the $\Delta P/P$ parameter. The control was used with the Pace simulation. No attempt was made to control the engine by using the loop.

GROUND LEVEL ACCELERATION AND DECELERATION TESTS

Ground level tests to demonstrate operation on $\Delta P/P$ parameter consist of:

- Establishing schedule bounds.

- Adjustments for accelerations on both integral and proportional control loops.

- Adjustments for decelerations on both integral and proportional control loops.

Operations of the engine during the tests are presented by Figures 19 through 27.

Schedule Bounds

The scheduled parameter is ratios (W_f/P_3). The effect on performance of the ratios parameter was established and allows bounds to be set on maximum and minimum ratios. These bounds may be retained if desired when investigating any other loop and will act as an engine safety control.

Some of the control flexibilities were demonstrated in these runs. Ratios may be scheduled by RPM for either acceleration or deceleration. Also it is possible to set an increment above or below a reference (base ratios) value.

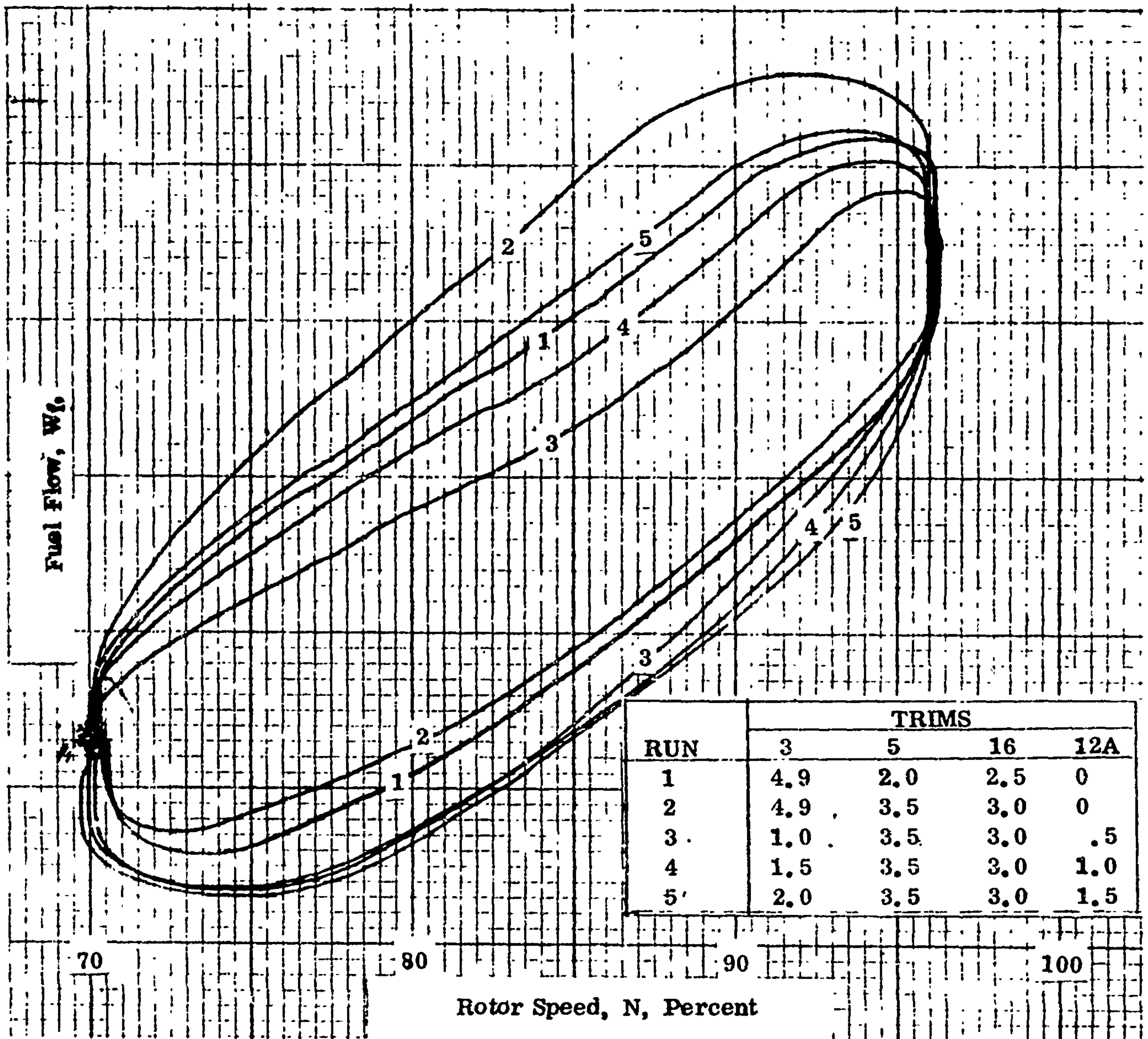
The system also includes the ability to control the rate of change of the parameter (ramp rate). This feature is used to control the initial transition from a steady state point to transient control, thus preventing excessive overshoots when establishing transient control of the system.

Schedule bounds computations are shown by Figure 9. Figure 18 illustrates the effect of schedules in ratios (W_f/P and the effects of scheduled ramps or integration rates and the effects of steps in ratios added to the base ratios. Run 1 is the acceleration and deceleration at the normal start settings.

For Run2 the maximum ratios were increased to a setting of 3.0 volts and the deceleration ratios were increased to 3.5 volts. At these settings the acceleration occurs in about .8 second and the deceleration occurs in about 2.1 seconds.

Runs 3, 4 and 5 show the effect of steps in ratios added to the base ratios. These steps are parallel effects with the maximum ratios. For the setting of run 3, the step is one volt and the acceleration occurs in about 2 seconds.

Runs 3, 4, and 5 show the effect of integrating the ratios ramp setting on deceleration. For run 5, a ramp setting of 1.5 volts is used and the deceleration occurs in .8 second.



RUN	TRIMS 3	5	16	12A
1	4.9	2.0	2.5	0
2	4.9	3.5	3.0	0
3	1.0	3.5	3.0	.5
4	1.5	3.5	3.0	1.0
5	2.0	3.5	3.0	1.5

Figure 18 -- Ratios (W_f/P) Bounds

Acceleration Control by Integration

Computations for acceleration control on airflow ($\Delta P/P$) are shown by Figure 11. Acceleration control from various speed points and the effect of schedule ramp are shown by Figure 19. Prior to these runs, the gain in integration of ratios with error in scheduled $\Delta P/P$ was varied to establish a desired gain setting. Also a low scheduled ramp was used. Run 1 illustrates the low gain of .5 volt. The scheduled ramp trim 4 was also set at .5 volt and as a result had influence at the start of the acceleration. The scheduled ramp was increased to 1 volt for run 2 and to 1.5 volts for run 3. The scheduled ramp effect was thus eliminated as an influence on the acceleration.

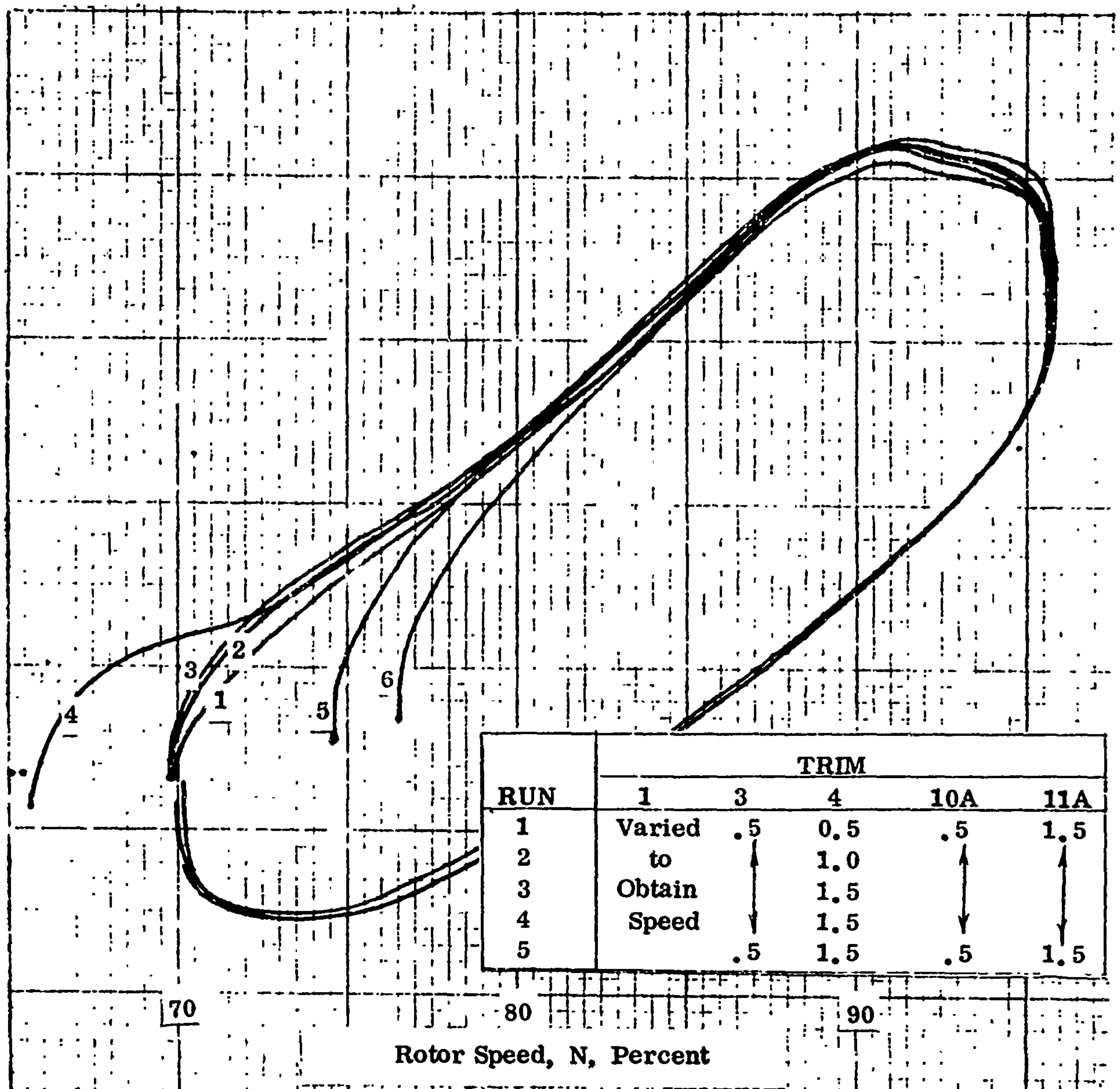
With the setting of run 3, the idle trim adjustment was varied to start the accelerations from various speed points. The fuel was controlled to a very narrow band during this demonstration.

At steady state idle, the $\Delta P/P$ sensor voltage was adjusted to about 4.4 volts. The ramp of fuel-pressure ratios depends on the setting of the desired control voltage. Figure 20 illustrates the effects of increasing the control voltage (Trim 11A) nearer the steady state value. Run 1 is a repeat of run 3 from Figure 19. For run 2, the control voltage trim 11A was adjusted to 2.0 volts. Figure 21 is a time trace of these runs which illustrate the initial overshot of the sensor and then control near the set value for the remainer of the transient.

For runs 4 and 5 the control setting of the $\Delta P/P$ sensor is nearer the steady-state value. The slower acceleration allowed time for a second oscillatory loop during run 4. For run 5, the gain was doubled allowing twice the ramp rate. This caused a rather violent flow oscillation with the mean near that required to obtain the requested $\Delta P/P$ sensor output. It is evident from these traces when considered with the runs of 1, 2 and 3 of Figure 19 that the computations as defined with control over the initial rate of fuel increase is necessary to prevent a large initial overshoot.

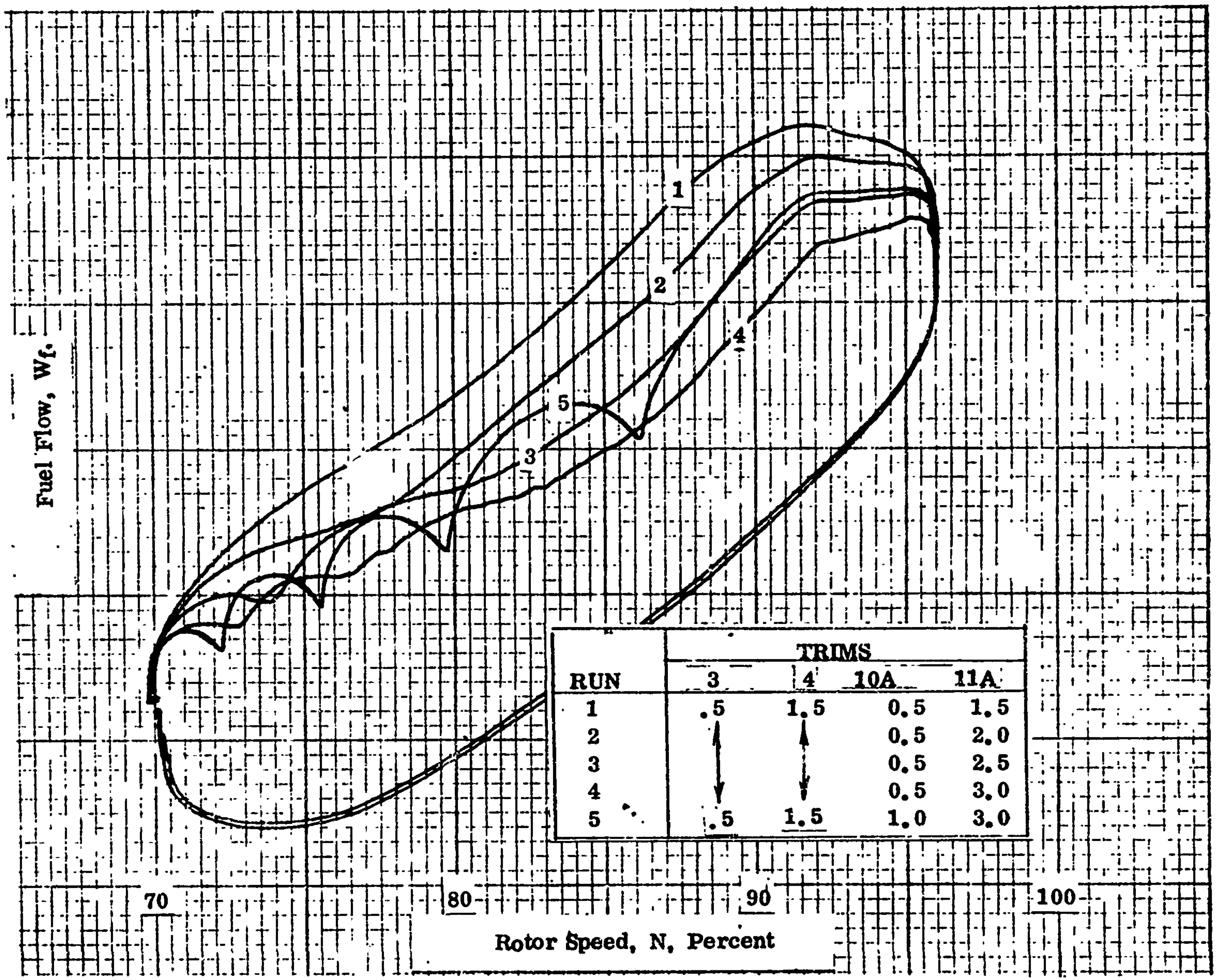
ACCELERATION CONTROL BY PROPORTIONAL ACTION

Control computations for airflow ($\Delta P/P$) proportional control are illustrated by Figure 11. For this control a value of $\Delta P/P$ is set so that the sensor voltage moves from steady state past the set voltage and the difference causes a reduction in the maximum ratios schedule by the adder and select low loop.



RUN	TRIM 1	3	4	10A	11A
1	Varied	.5	0.5	.5	1.5
2	to		1.0		
3	Obtain		1.5		
4	Speed		1.5		
5		.5	1.5	.5	1.5

Figure 19 -- Acceleration Control by Integration



RUN	TRIMS 3	4	10A	11A
1	.5	1.5	0.5	1.5
2	↕	↕	0.5	2.0
3			0.5	2.5
4			0.5	3.0
5	.5	1.5	1.0	3.0

Figure 20 -- Instability of Acceleration Control by Integration

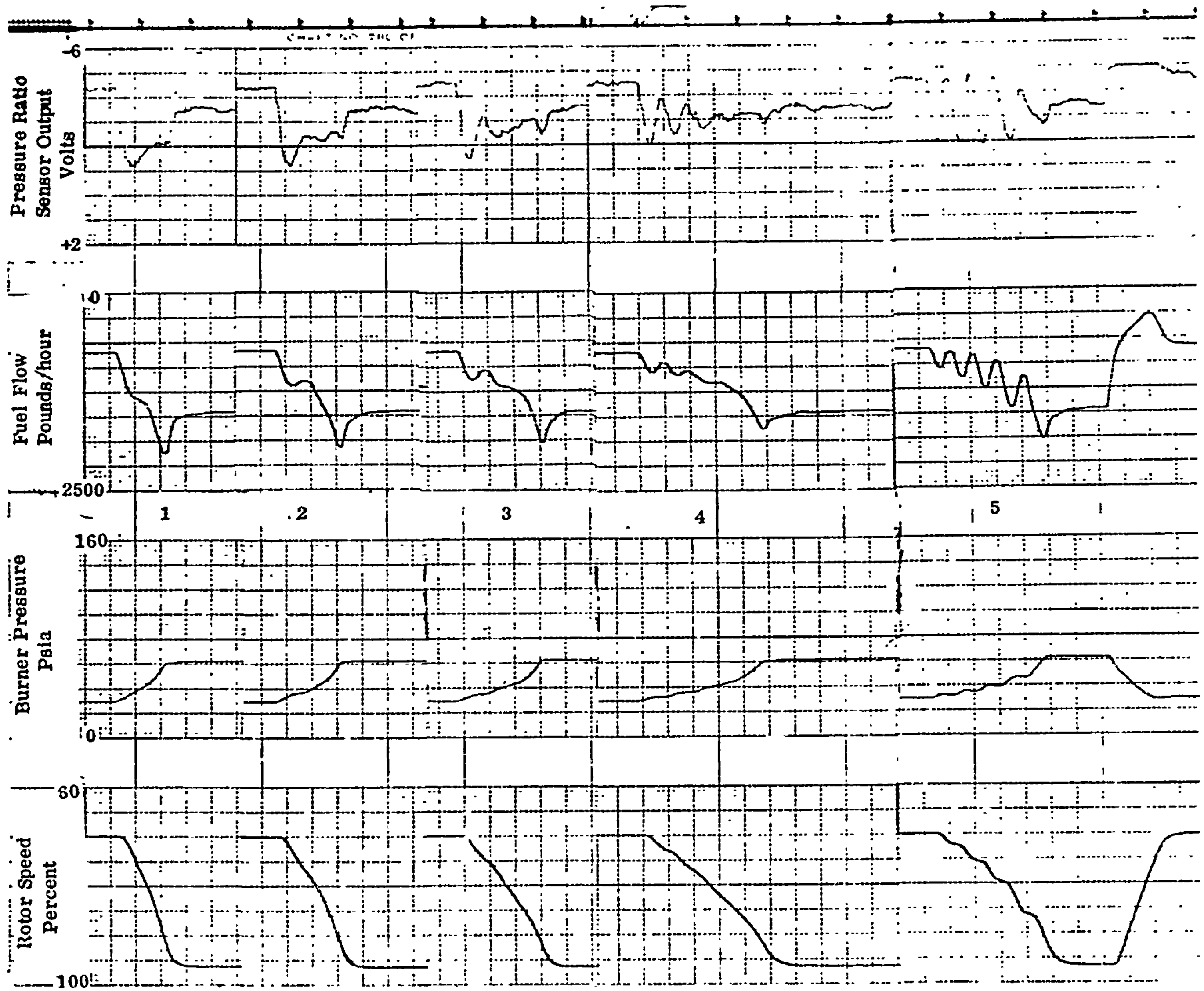


Figure 21 -- Time Traces of Acceleration by Integration

Figure 22 illustrates control on the proportional control. Run 1 is identical to run 1 of Figure 20 which is controlled on the integration system. Trims 10 and 15 were set to make the proportional control effective. This caused a lower fuel flow around 72% speed but then increased above the flow of run 1. For run 3 the integration control was reference set lower to increase the integration rate. The loop was then slightly oscillatory. For run 4 the proportional control reference was set at 2.5 which is nearer the steady state value. This caused greater oscillation than run 3 primarily due to the initial overshoot of the set point.

The gain setting for run 5 was changed to 1.0 volt. This caused the trace to be higher than the other traces after an initial low value. The setting for run 5 was used for the three runs of Figure 23.

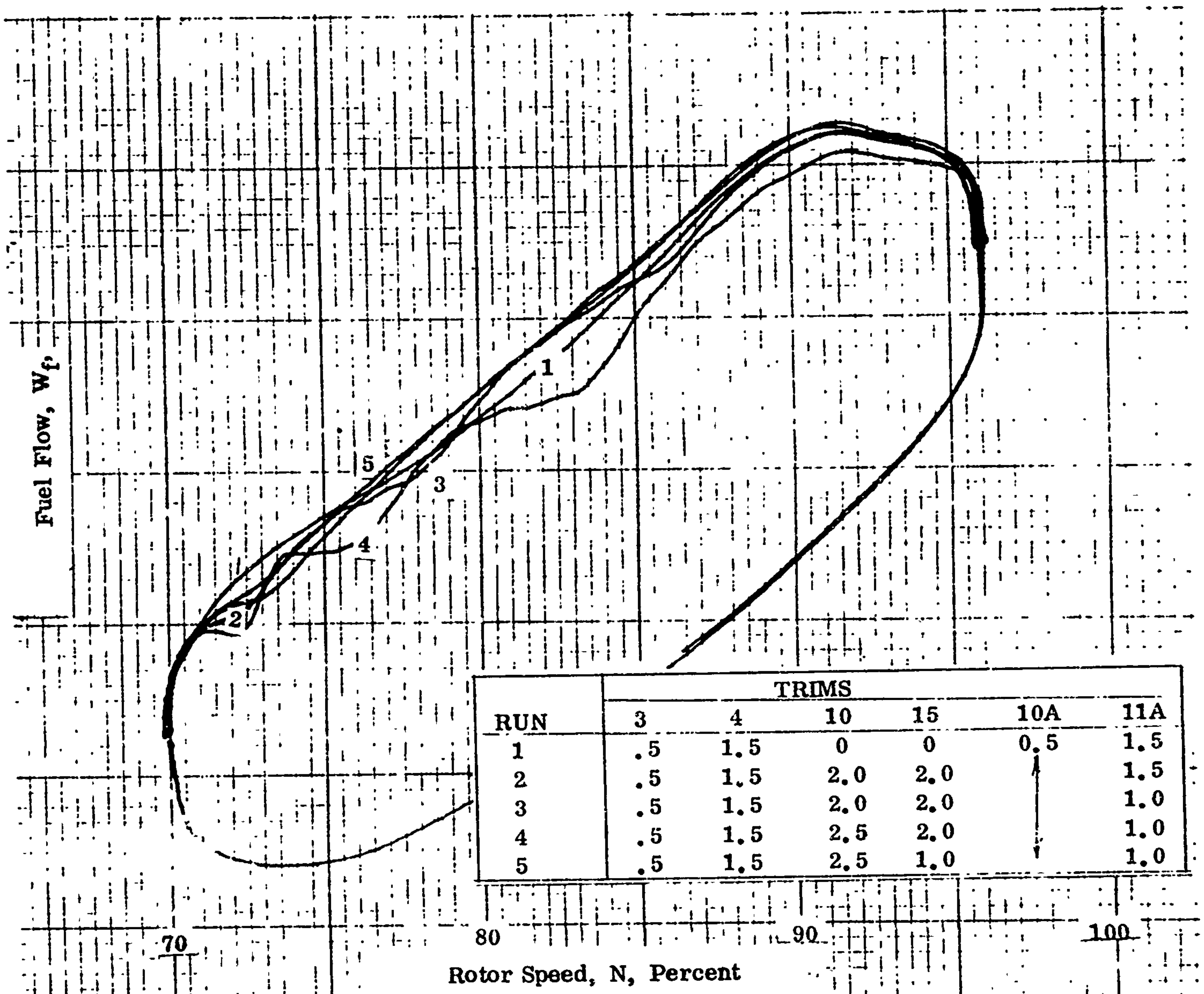
Figure 23 illustrates control from three speed points. The spread obtained in the three lines is due to a combination of effects. For stable control the gain was low. The initial scheduled step and ramp to prevent large overshoots is more effective at the higher speeds where the acceleration time is short. The rate of the fuel valve also appears to have some effect during rapid accelerations.

Deceleration by Proportional Control

Control computations for deceleration control on the airflow parameter are illustrated by Figure 12. It is observed that deceleration control is restricted to a ratios band of 350 counts. Figure 24 runs 1 and 2 illustrate the band of operation.

For run 3, the proportional loop was made effective by change of the gain from zero to 2.5 volts. At this setting the loop was very oscillatory so the gain was changed to 1.0 volt. At this setting, the trace was less oscillatory and the fuel level was somewhat lower. For run 5 the reference level was changed to 3 volts from 4 volts. This was a setting to require a higher flow during the deceleration. The deceleration ratios setting was than changed from 2.5 to 4.9 which is a setting of higher fuel flow during the deceleration.

Time traces of runs 1 and 2 of Figure 24 are shown by Figure 25. The $\Delta P/P$ sensor was readjusted until the output was against the stop during steady state. During trace 1, the deceleration flow was high, and the $\Delta P/P$ sensor output moved from +1.4 to -1.4 volts. During trace 2, the decleration flow was low, and the sensor output moved to the stop at -4.9 volts. The other traces of Figure 25 show the transients from various speed points.



RUN	TRIMS 3	4	10	15	10A	11A
1	.5	1.5	0	0	0.5	1.5
2	.5	1.5	2.0	2.0		1.5
3	.5	1.5	2.0	2.0		1.0
4	.5	1.5	2.5	2.0		1.0
5	.5	1.5	2.5	1.0		1.0

Figure 22 -- Acceleration by Proportional Control

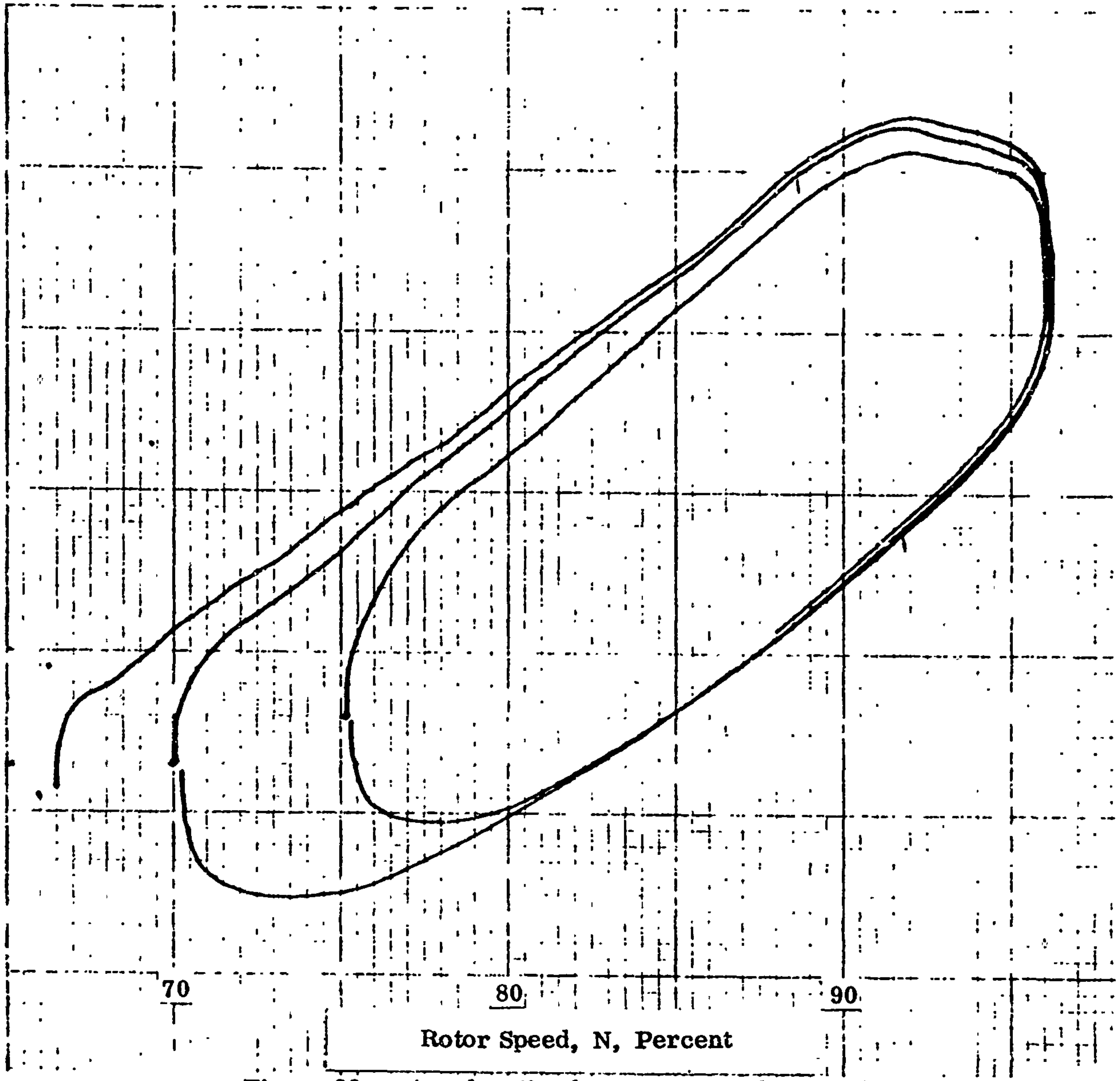
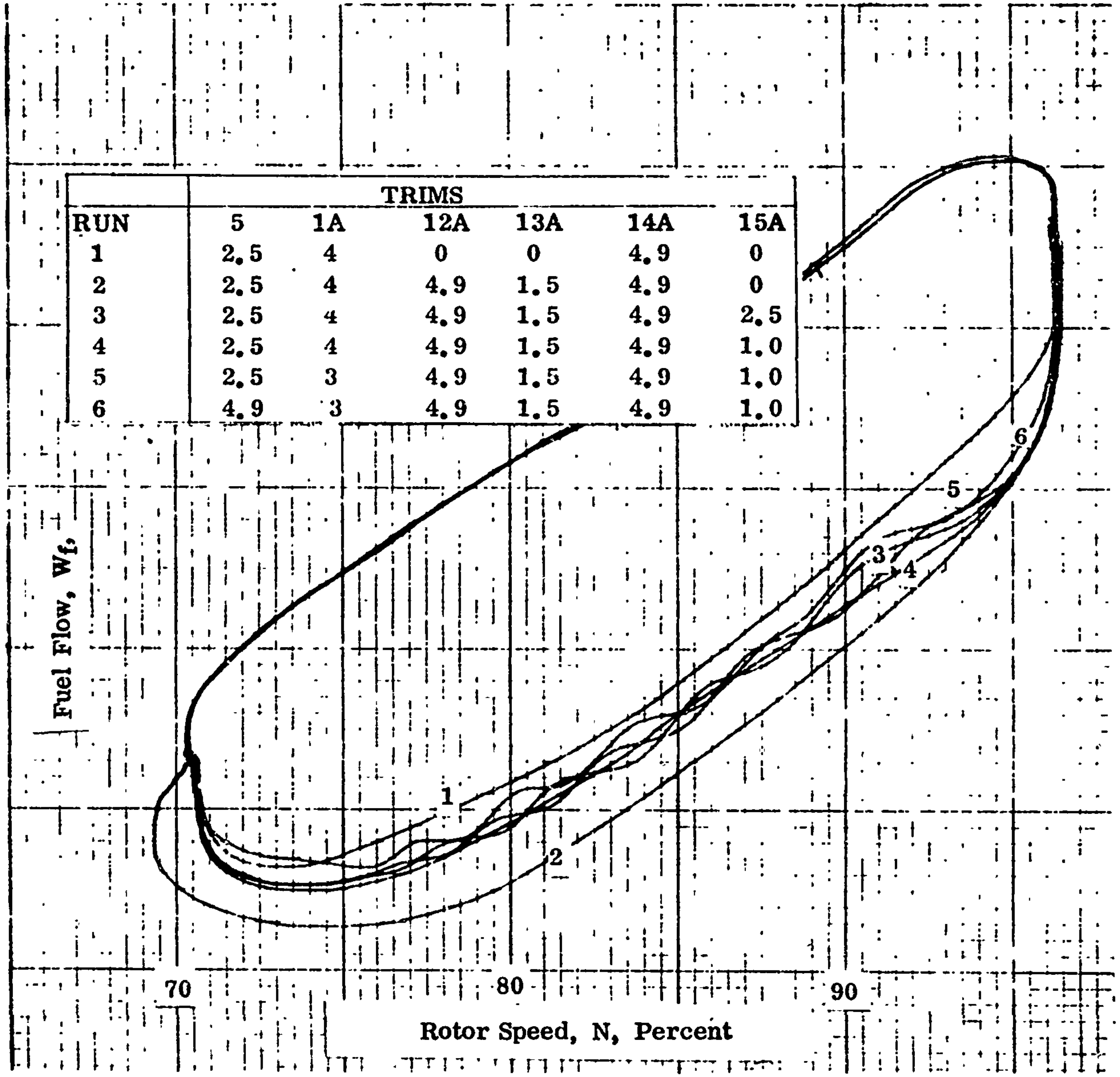


Figure 23 -- Acceleration by Proportional Control From Three Speed Points



RUN	TRIMS 5	1A	12A	13A	14A	15A
1	2.5	4	0	0	4.9	0
2	2.5	4	4.9	1.5	4.9	0
3	2.5	4	4.9	1.5	4.9	2.5
4	2.5	4	4.9	1.5	4.9	1.0
5	2.5	3	4.9	1.5	4.9	1.0
6	4.9	3	4.9	1.5	4.9	1.0

Figure 24 --- Deceleration by Proportional Control

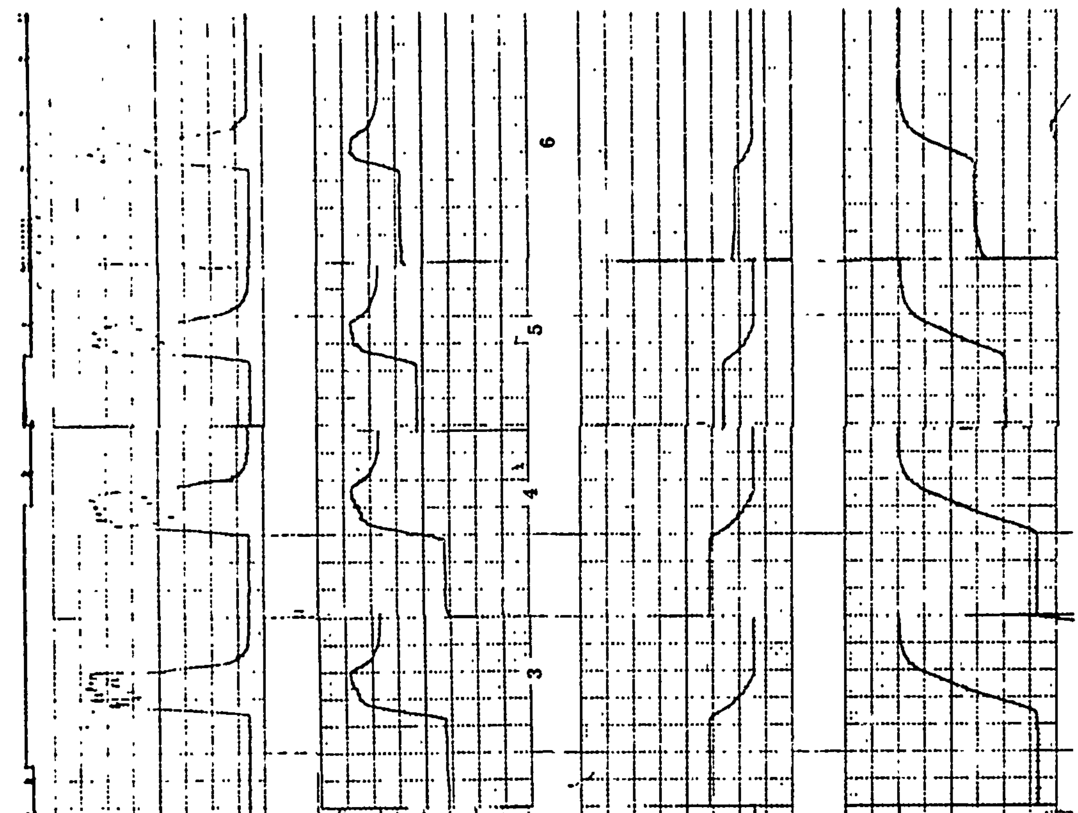


Figure 25 -- Time Traces of Proportional Deceleration Control

Figure 26 illustrates, proportional control trim effects and the traces obtained from several speed points. For run 1 the deceleration scheduled ramp trim 12A was set at 4.9 volts. This caused a most rapid decrease in fuel at the start of the deceleration, an undershoot in flow and then control. For run 2, the ramp was set to .5 volt and the initial decrease in fuel was much less and control smoothly started to act. For run 3, the ramp was changed to 1.0 volt, and the gain trim 15A was changed to .5 volt from 1.0. Then for run 4 the $\Delta P/P$ deceleration reference was changed from 3.0 volts of the previous runs to 2 volts.

Traces 3 and 4 of Figure 25 shows the effect of setting the control level from 3.0 volts to 2.0 volts. The change is not great in fuel flow, but the oscillation of the sensor output at approximately nine cycles per second is much more violent. The traces 5 and 6 shows deceleration from 90 and 84.5 percent speed. The deceleration band is fairly narrow and the fuel oscillations are at a tolerable level.

Deceleration Ratios Ramp Control

Figure 12 includes the computation for the deceleration ramp control. Three trims are used for this control loop: a scheduled ramp trim 12A, the closed loop ramp gain trim 13A and the closed loop ramp level trim 14A.

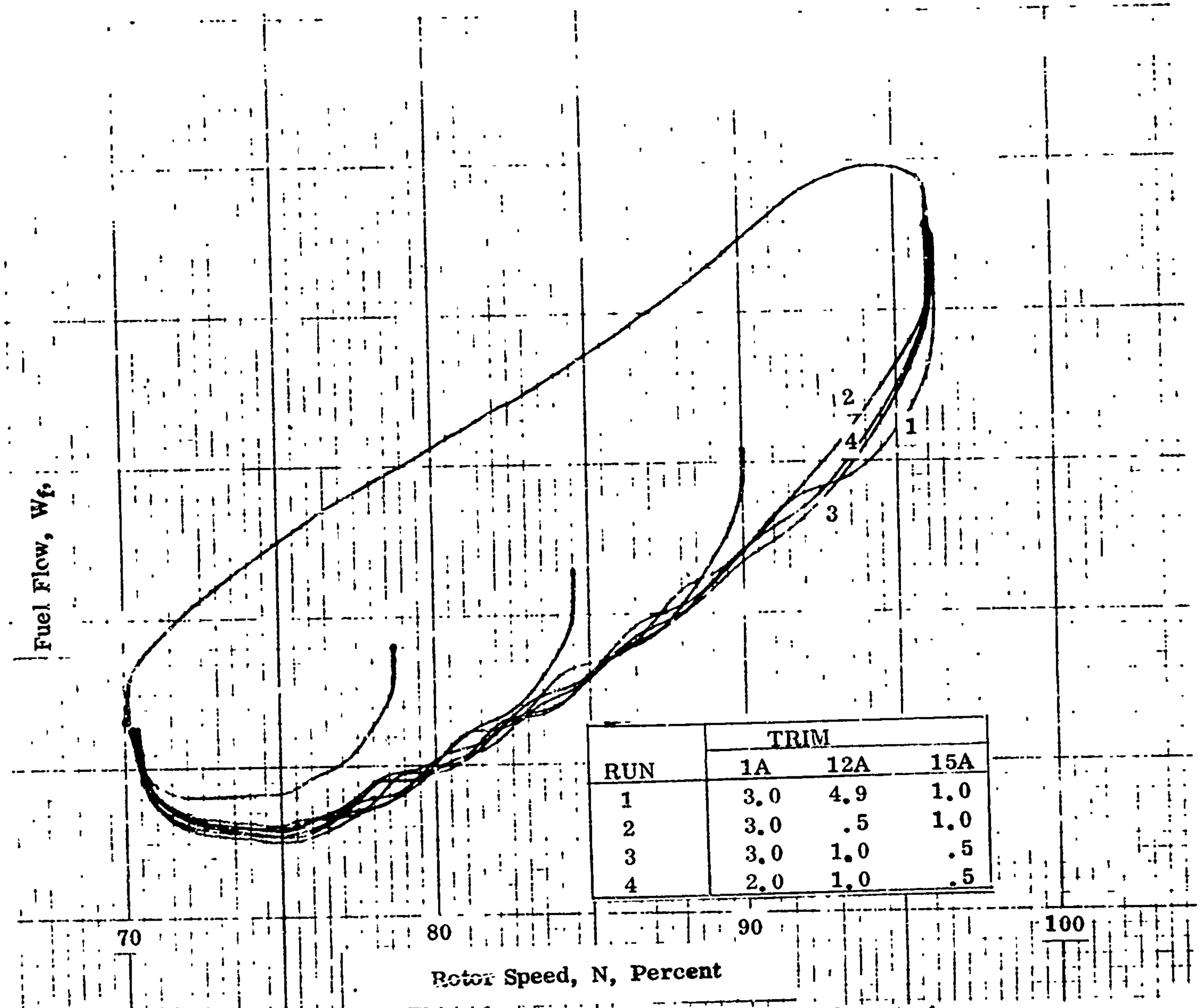
Figure 27 illustrates the deceleration control by integration. The frequency of oscillation during these decelerations was near 2.25 cycles per second. The schedule ramp trim 12A was changed from .5 to .75 to 1.0 volt for runs 1, 2 and 3. The setting of 1.0 appeared to allow most effective control on the closed loop. Decelerations were then made from four other speed points.

ALTITUDE TESTS

The engine was run at the equivalent pressure of 20,000 ft altitude. Figures 28 through 32 show the results of these tests. Output of the sensor changed more with speed at altitude than at ground level conditions. The sensor, however, could be adjusted to provide a band of control for acceleration and then readjusted to obtain a band of control for deceleration. The longer time of the transients resulted in more obvious control at the set point of the parameter.

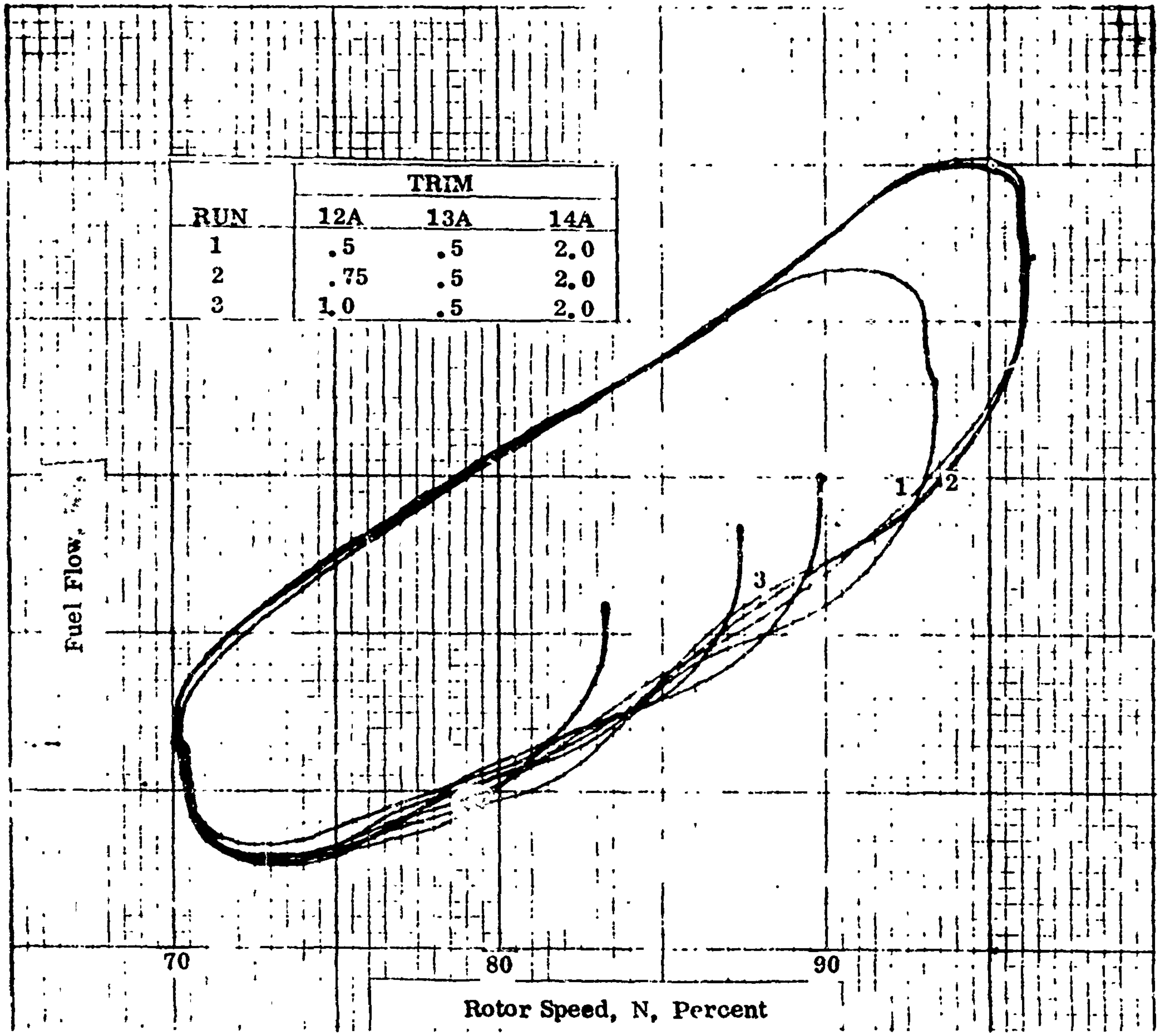
Altitude Acceleration Control by Integration

Figures 28 and 29 illustrate the accelerations and the effects of trims for integration control. The scheduled step and ramp were set at .75 and .5 volt respectively. This step setting causes the undershoot in speed during the decelerations. The small step is near the required to run.



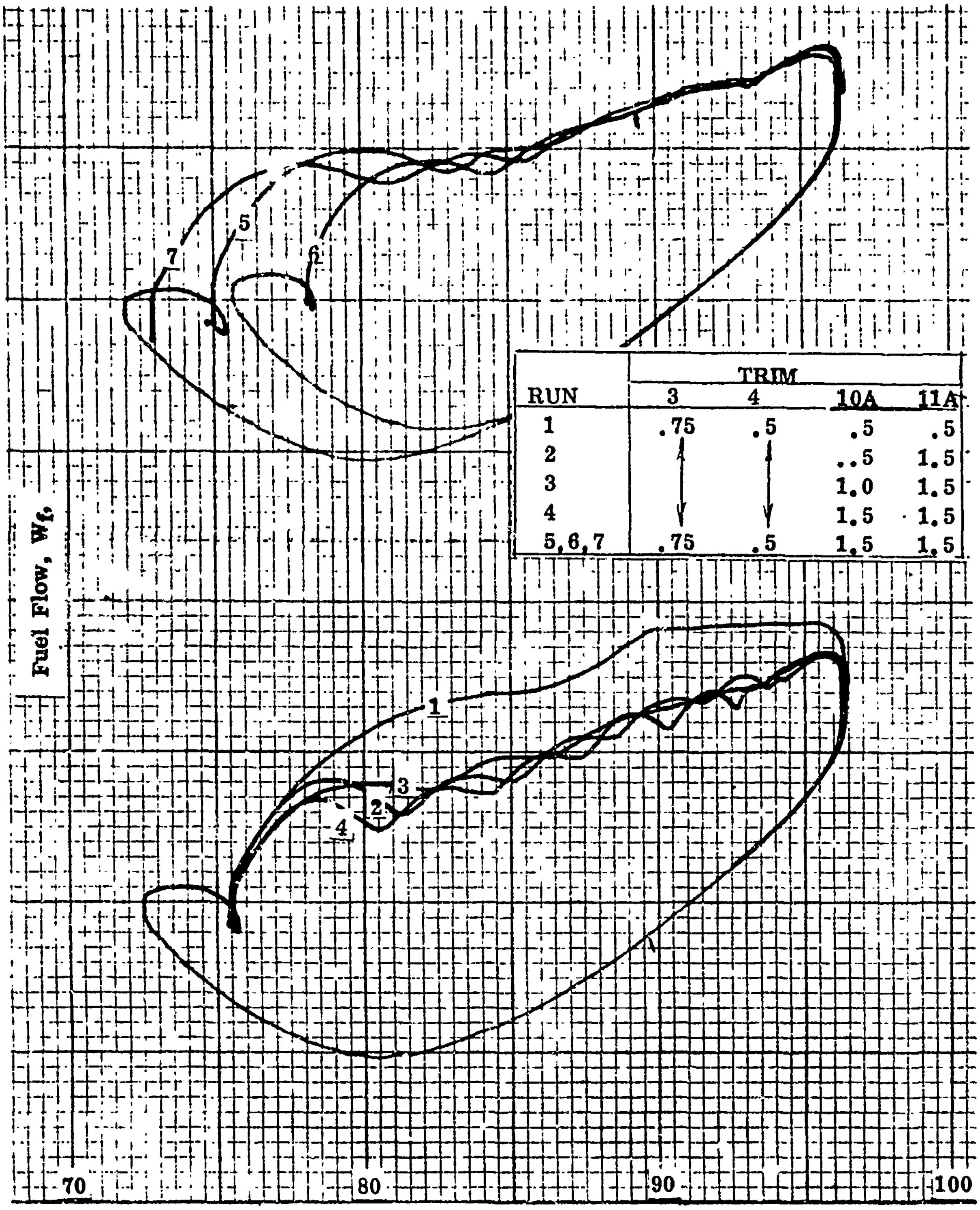
RUN	TRIM 1A	TRIM 12A	TRIM 15A
1	3.0	4.9	1.0
2	3.0	.5	1.0
3	3.0	1.0	.5
4	2.0	1.0	.5

Figure 26 -- Deceleration by Proportional Control From Several Speed Points



RUN	TRIM 12A	TRIM 13A	TRIM 14A
1	.5	.5	2.0
2	.75	.5	2.0
3	1.0	.5	2.0

Figure 27 -- Deceleration Control by Integration



RUN	TRIM 3	4	10A	11A
1	.75	.5	.5	.5
2			.5	1.5
3			1.0	1.5
4			1.5	1.5
5,6,7	.75	.5	1.5	1.5

Figure 28 -- Altitude Acceleration Control By Integration

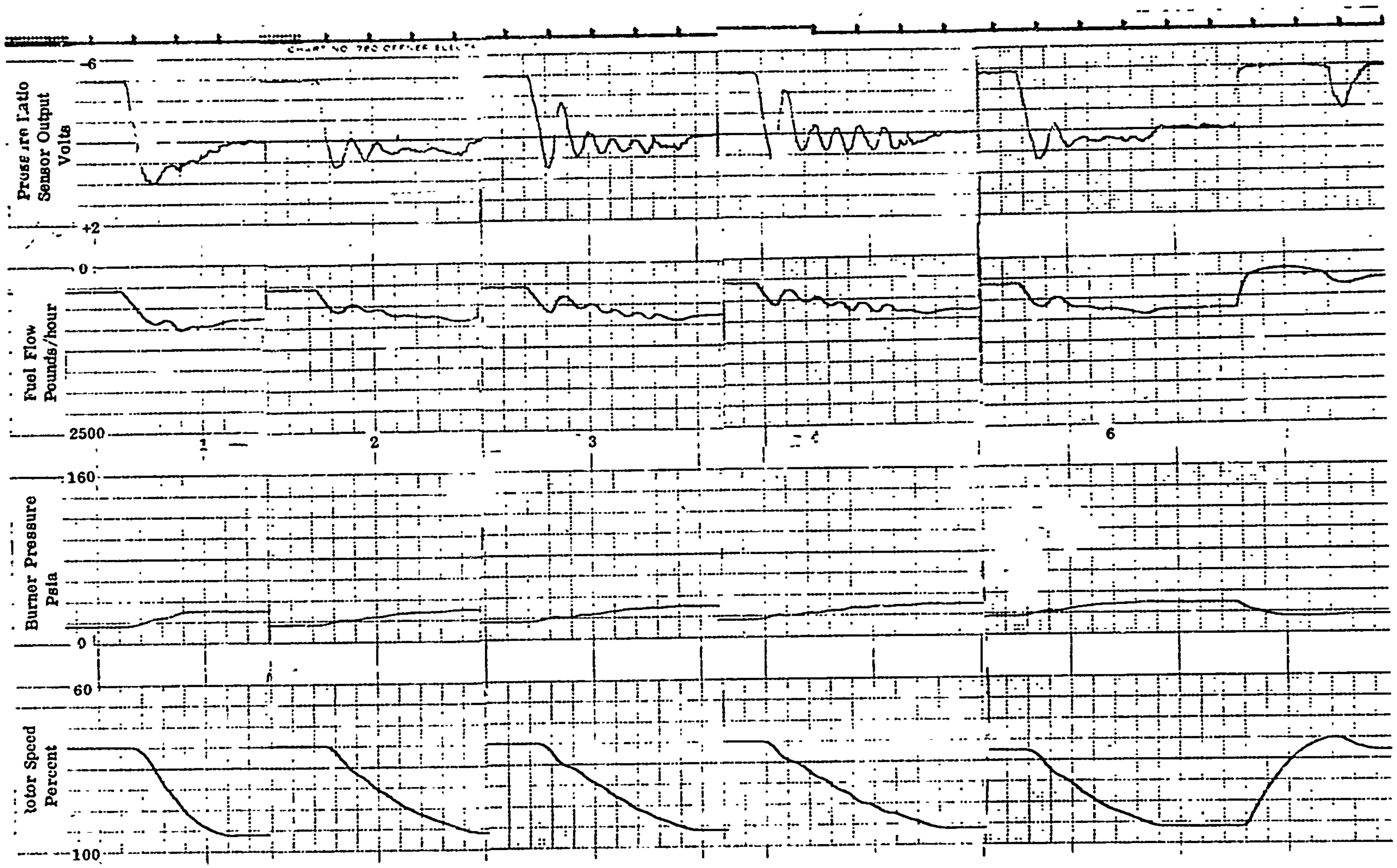


Figure 29 -- Time Traces of Altitude Control by Integration

At the low burner pressure of the deceleration, the fuel flow remains low until the ramp becomes effective at about 4 percent underspeed.

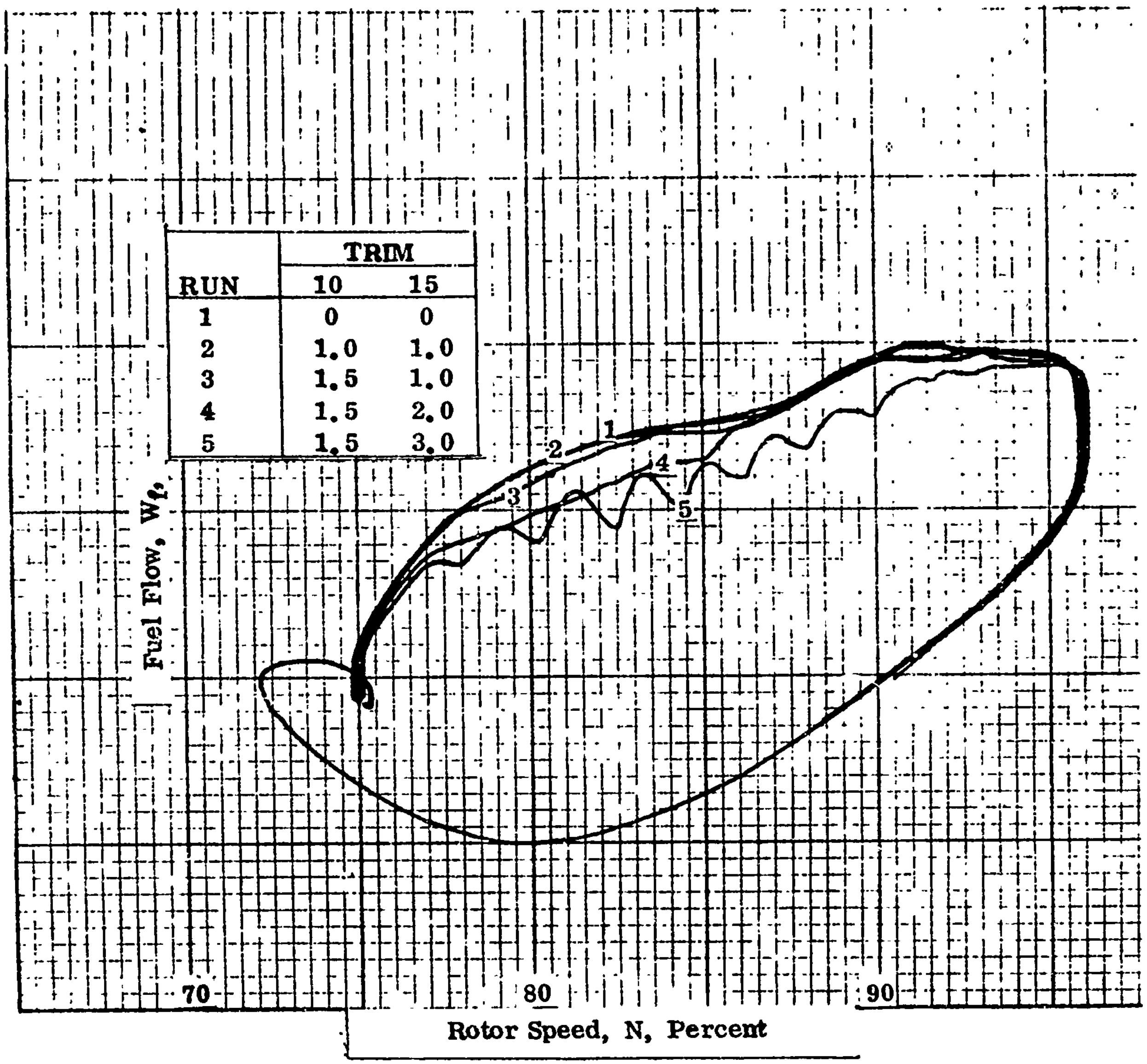
Runs of the lower group of traces of Figure 28 were used to establish the setting for the upper group. For run 1, the ramp control reference was set at zero. The sensor output reached this level and then decreased as the engine accelerated on the maximum scheduled ratios. The flat near the end of the acceleration is caused by the burner pressure control. The burner pressure was set at .75 volts equal to 37.5 psia for some safety during engine starting. The setting was left there. When the 37.5 psia pressure was reached, the burner pressure control maintained the pressure and since the acceleration was at maximum ratios (a constant), the fuel flow remained constant.

For the other transients, the control sensor request was changed to -1.5 volts. Operation was then around that value of the sensor output. With the higher gains of trim 10A, the control was much more oscillatory than at the 0.5 volt value used for the accelerations from the three different speed points. The initial overshoot in fuel was much greater at altitude condition than at the ground level condition shown by Figure 19. The rate of the fuel valve has some effect at ground level, but since the total travel required at altitude is much less, the value rate is not an effect at altitude.

Altitude Acceleration by Proportional Control

Accelerations by proportional control are shown by Figure 30. For runs 1 and 2, there was very little control because of the level of control set by trim 10. For run 3, there was very little control because of the low gains. When the gain trim 15 was increased to two volts and three volts for runs 4 and 5, the gain was high enough for control.

Run 6 of Figure 29 illustrates the change in the sensor output (3 volts) between 77 percent speed and 95 percent. Also run 1 illustrates the acceleration characteristics in the higher speed range with the sensor output only slightly greater than steady state at the 95 percent speed point. Only run 5 of Figure 30, the high gain setting of trim 15 on the control, had an effect in the high speed range. Control was obtained by run 4 in the lower speed range. When the level of control trim 10 was changed to a higher voltage magnitude, the control setting was within the range of steady state values and would prevent acceleration to maximum power.



RUN	TRIM 10	TRIM 15
1	0	0
2	1.0	1.0
3	1.5	1.0
4	1.5	2.0
5	1.5	3.0

Figure 30 -- Altitude Acceleration by Proportional Control

Altitude Deceleration Control by Integration

Deceleration control by integration is shown by Figure 31. For these runs the deceleration control level trim 14A was varied to show the effect of the control. Control is similar to the control at ground level Figure 27. The sensor is less responsive at the low pressure levels associated with the altitude deceleration transient. Control action behavior reflects the increased time constant of the sensor.

Altitude Deceleration by Proportional Control

Deceleration by proportional control is illustrated by Figure 32. These deceleration transients are similar to those of Figure 31. Control action is similar to the ground level transients of Figure 24. Control response is limited by the slow response of the pressure ratio sensor. Further the control action reflects the change of sensor output with speed which occurs at altitude.

STALL TESTS

The engine was stalled by closing the bleeds while the control was maintaining a constant speed. Three stalls are presented by Figure 33.

For stall number one the fuel was being oscillated at one cycle per second with an amplitude of ±60 pph. The bleeds were being slowly closed from the open position of about 1.6 volts toward the closed position of about 4.16 volts. The stall is evident by an abrupt decrease in burner pressure. There was also a rapid rise in the tailpipe temperature indication. This indication is monitored by the engine operator. When stall occurred, the pressure ratio output moved in the direction to indicate a decelerating condition associated with a fuel reduction. Fuel decreased very little during the transient. The fuel was at a value to maintain the speed before the stall. When stall occurred, the pressure decreased and simultaneously the decrease in speed caused the request fuel-pressure ratios to increase to the maximum set value.

Speed decreased to about 55 percent before recovery. The transient in pressure ratio sensor output from near -5 volts to +1 volt is due both to the acceleration fuel flow and to the decrease in airflow with lower rotor speed. Behavior of the sensor as the rotor increased back to speed is a normal transient during all engine start ups.

Change in engine variables between the conditions which cause stall and normal steady state conditions is evident between stalls 1 and 2. The pressure ratio sensor output indicated greater airflow before stall than the normal steady state airflow.

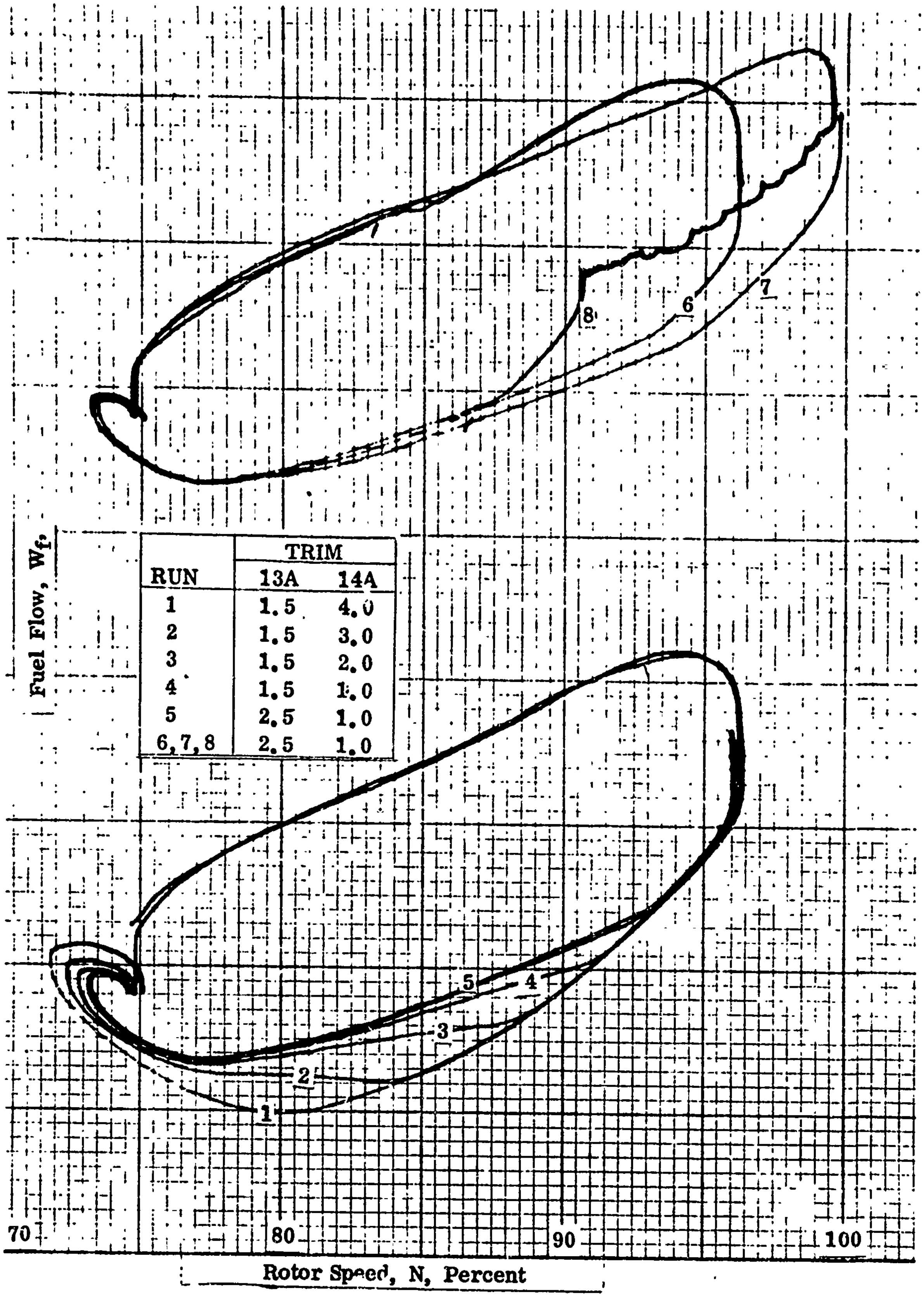


Figure 31 -- Altitude Deceleration Control by Integration

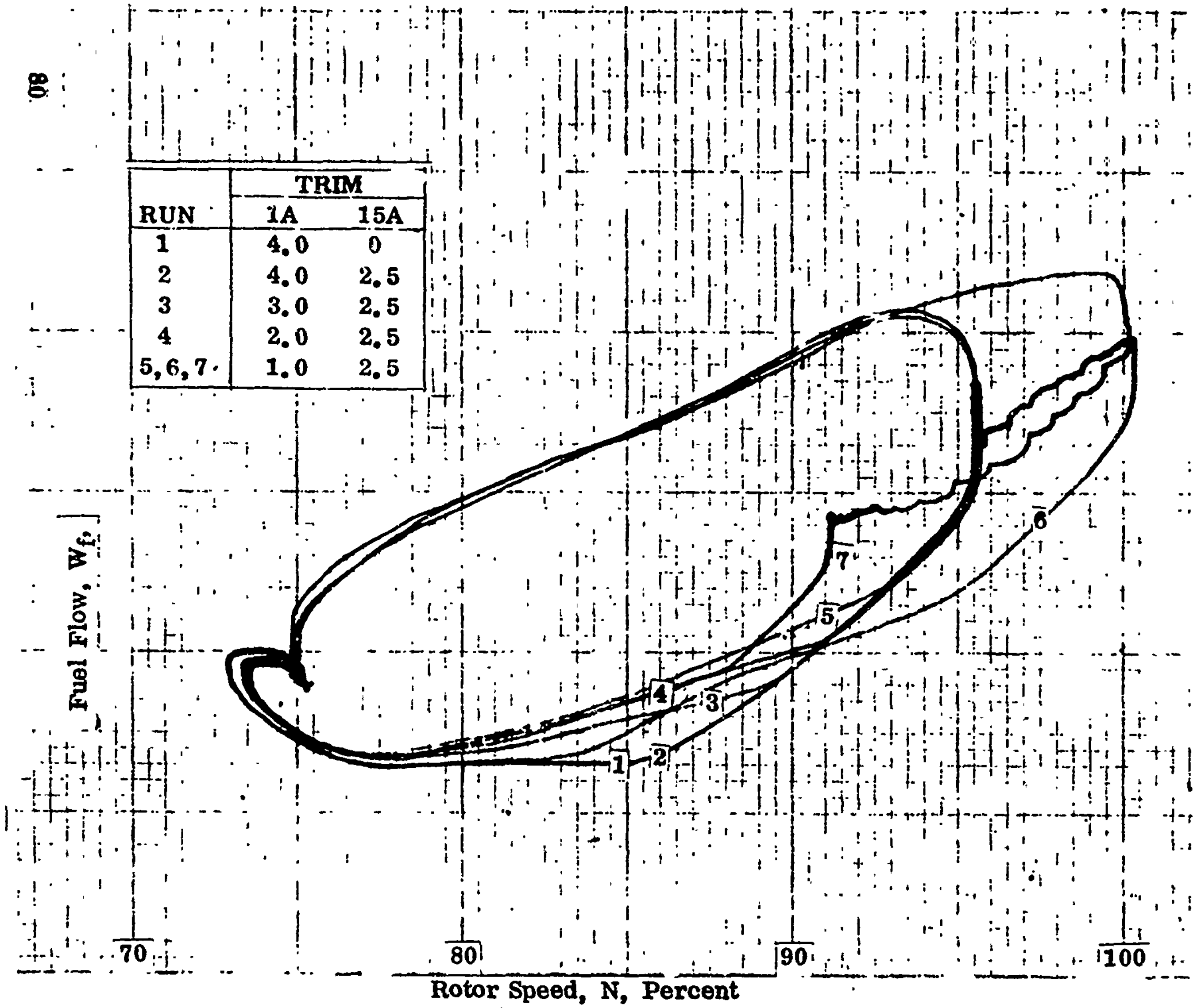


Figure 32 -- Altitude Deceleration by Proportional Control

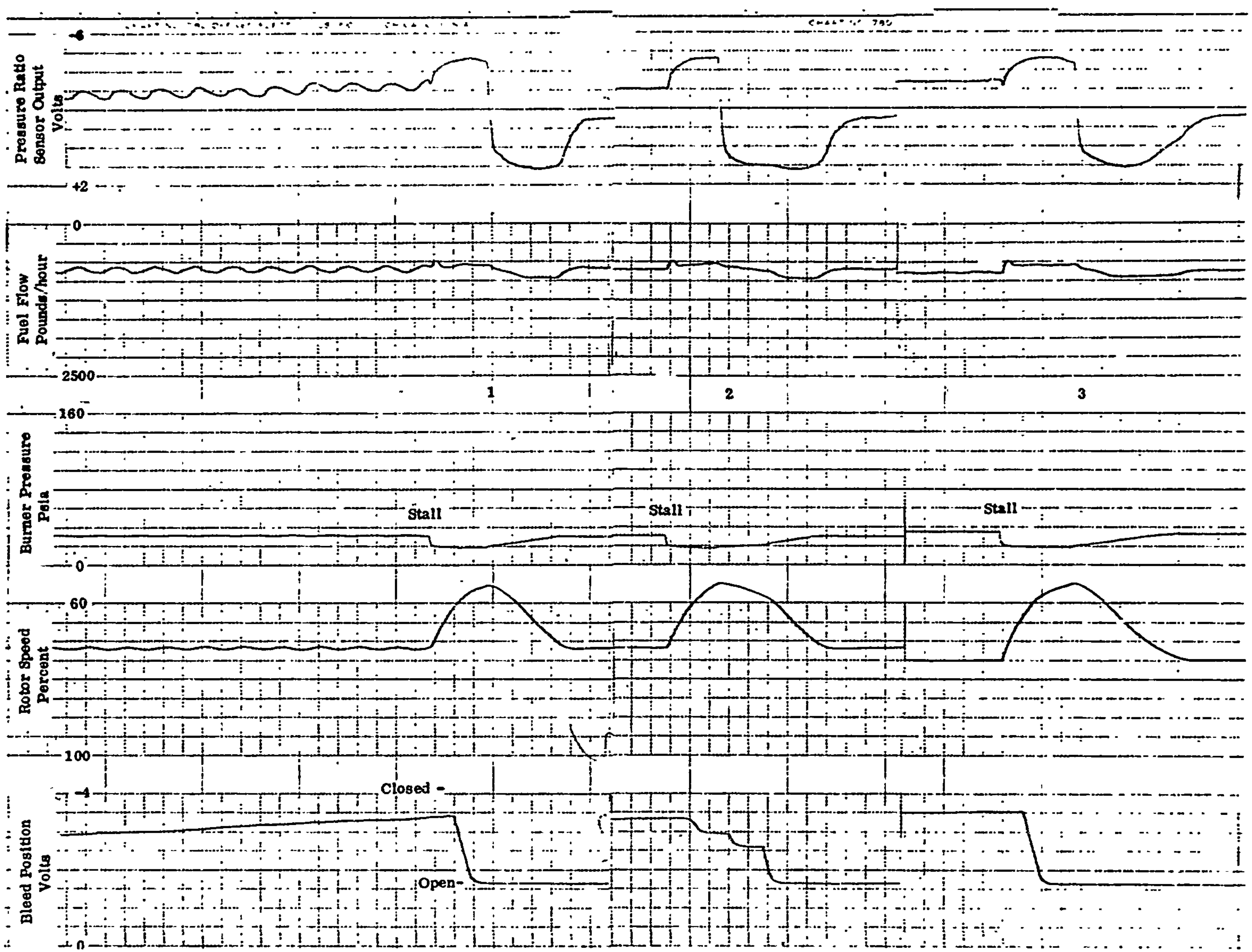


Figure 33 -- Time Traces of Engine Stalls

Recovery from stall during the second transient was different from the first because of the bleed control movement. The bleeds were manually moved toward the closed position and after stall in the first case the bleed control was switched back to computer control. After the second stall, the bleeds were manually opened part way and then switched.

The third stall was from 75% speed. Fuel flow decreased after the stall in this case because the fuel was higher before stall but the pressure decreased to about the same level during the transient.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

A jet engine parameter for closed loop control of the engine transients was investigated and tested in the program being reported. The parameter investigated was based on the concepts of airflow corrected to compressor discharge conditions. The parameter used to infer airflow was a combination of pressures sensed between the last rotor and the burner and is designated $\Delta P/P$ throughout this report. The $\Delta P/P$ parameter was sensed with a fluidic device. Wall static pressure between the compressor and burner was used for high pressure. The pressure sensed by static probe located in the last stator row was used for low pressure.

A special control system was defined, assembled, and used to evaluate engine performance with closed loop accelerations and decelerations on the $\Delta P/P$ parameter. The special control system was conceived and implemented with an IBM 1800 digital computer used for control computations. A hydromechanical fuel valve, sensors, and an interface/adjustment electronic package used in conjunction with the digital computer completed the special control system.

Analysis of the J85 engine indicated, and test confirmed, that the $\Delta P/P$ parameter can be used for closed loop engine fuel control during transients. The analysis of other engine compressor maps indicate that, in general, the $\Delta P/P$ reference value would have to be shaped as a function of corrected speed for application to a control system closed loop. To define a control using $\Delta P/P$ as the acceleration parameter, the engine involved would have to be tested to determine sensor probe location and $\Delta P/P$ characteristics during an acceleration.

This test program included altitude testing of the $\Delta P/P$ parameter. Test showed a difference in the parameter value at altitude relative to sea level tests. It would be necessary to establish a sensor probe location that minimizes or eliminates this altitude effect prior to an application of $\Delta P/P$ in a control system.

CONCLUSIONS

- The compressor map for the J85 indicated $\Delta P/P$ would be constant during acceleration from 60 percent to 100 percent engine rpm. At less than 60 percent engine rpm the parameter at the stall line decreased rapidly. The test range for closed loop control was limited to the idle to maximum engine rpm operating range and special scheduling was used for the engine start to idle transient.

  During decelerations, the corrected air flow increase from steady-state values, and since the steady-state value is nearly constant, a constant value was used to demonstrate deceleration control on the parameter.

- A more responsive pressure ratio sensor was obtained by modifying the sensor used during the tests of Reference 1. Sensor integration rate was increased from 0.5 to 1 inch/second over the test pressure levels to 2 to 3 inches/second. The sensor thus followed the fuel transients with a small lag of about 0.02 second.

- Transient control on the parameter could be accomplished at simulated altitude (20,000 ft) as well as at ground level. There was a greater steady state variation in the parameter at altitude than at ground level. Demonstration of control was accomplished by adjustment of the sensor for accelerations and readjustment for decelerations.

- Stalls were obtained by closing the bleeds and opening the guide vanes by the interconnected linkage at 70 and 75 percent speed. No change in the $\Delta P/P$ parameter and no change in the noise on the burner pressure as observed on an oscilloscope was detected before stall. During the stall output of the sensor indicated a higher airflow, a condition farther from stall, and the scope pressure signal became noisy.

- Repeatability and predictability of the control system assembled was excellent. The system can readily be adapted to various tests with assurance that the control interface and computer program will perform.

- In addition to demonstrating the $\Delta P/P$ loop, control functions normally associated with a fuel control system were demonstrated. Also the flexibility of the electronic package and the IBM 1800 Computer to vary schedules easily and rapidly was demonstrated.

Factors demonstrated included:

- Starting control
- Acceleration scheduling
- Accelerations were scheduled on a three (3) segmented (W_f/P_3) fuel pressure ratios curve with $\Delta P/P$ loop set so as not to be a control.
- Deceleration scheduling
- Speed governing
- Burner pressure control
- Rapid and simple adjustments on:
  - Acceleration schedule
  - Deceleration schedule
  - Governor set point relative to throttle angle position
  - Governor gain
  - Start schedule

RECOMMENDATIONS

- Test data should be obtained in other engines for the purpose of evaluating the applicability of the $\Delta P/P$ parameter for acceleration control on a broader basis than can realistically be defined by tests on a single J85-7 engine.
- Isolate actuation of the vanes and the bleeds of the J85-7 engine to isolate the effects on stall conditions. Further, the two sets of bleeds could be isolated to obtain unbalanced flow conditions.
- Distort inlet to compressor to determine flow characteristics at the compressor discharge due to inlet flow distortion.

- Instrument compressor immediately before the bleeds as well as at the rear of the compressor with multiple sensing devices to ascertain effects of guide vanes, bleeds and distortion.

- Conduct more tests into stall at any time an engine is available and engine failures will not jeopardize other test programs. Stall characteristics of the J85-7 engine which was designed for high altitude operation are probably not representative of most engines. Tests into stall of the J85 at higher speeds and probably at altitude conditions are desired. Data of stall characteristics of other engines should be obtained.

SECTION VII

REFERENCES

1. AFAPL-TR-71-78, Electronic Engine Control Utilizing Compressor Exit Conditions for Acceleration Control, by S. E. Arnett, The Bendix Corporation, Energy Controls Division, November 1971.

2. AFAPL-TR-71-80, A Facility and Instrumentation for Studying Engine Control and Performance, by James E. Johnson, William J. Astleford, Jesse L. Holster, Robert L. Bass, III, C. Richard Gerlach, Southwest Research Institute, November 1971.

APPENDIX I

DESCRIPTION OF BENDIX EK15 AND EK14 ELECTRONIC INTERFACE PACKAGE

SYSTEM CONCEPTS

The Bendix Model EK15 Electronic Package is incorporated in a 19" x 20" x 62" rack. Bendix Model EK14 Electronic Package is included in the rack. Figures 4 and 5 show the front and rear views of the package. Rack features from bottom to top are:

- Two 8.75" storage drawers
- Power supplies for ±5, ±15, and 0-34 VDC,
- A convenience shelf,
- An 8.75 spare space,
- The EK15 circuit assemblies, and
- The EK14 package.

The package is connected into the control system by cables through the connectors shown by Figure 5.

System Assemblies and Components

The system is designed to control fuel to a G.E. J85-7 engine and to control compressor bleeds and guide vanes on the engine. Computations required are accomplished by the AFAPL IBM 1800 digital computer. Senses of engine variables are obtained by:

- A pressure ratio sensor (Bendix Model PRA-A1),
- Two CEC 4-326-0001 pressure transducers,

- A CEC 4-312-0002 pressure transducer,
- A parts list electromagnetic pulse generator, and
- A compressor bleed valve position potentiometer.

Fuel control is accomplished by positioning the metering valve of the Bendix EH-G1 fuel control flow section. Bleeds are controlled by a servo valve control of fuel flow to the bleed actuators. Fuel supply is obtained from the parts list fuel pump.

The AFAPL Pace Analog Computer Model TR48 is used for system checkout. An engine simulation is programmed and the computer provides signals as would exist from the engine through the interface signal conditioning circuits. The Pace computer signals are input to the signal isolation amplifiers. The simulated speed is conditioned by a voltage-frequency converter and input through the normal frequency to digital word circuit.

System components can remain connected while the simulation checkout is being performed. Further, the fuel control and bleed control can be operated by an auxiliary fuel supply during the checkout. The Pace computer input cable must be disconnected for engine running.

Package Inputs and Outputs

Figure 6 is a block diagram illustrating the inputs to and the outputs from the interface. Signal conditioning from input to output is accomplished by the various package circuits. A voltmeter, shown by Figure 4 is included in the package for monitoring the various adjustments and signals. Significant features include:

- Adjustments to the IBM 1800 computer program by voltage settings of potentiometers.
- Speed or frequency converters to provide digital numbers proportional to the reciprocal of frequency and voltages proportional to frequency.
- Five strain gage type pressure transducer circuits.
- Five position control circuits through torque motor driver amplifiers. These include the fuel valve control and the compressor bleed control.

- One pressure ratio sensor circuit.

- Provisions for computer program checkout by use of the Pace Analog computer.

- Three instrumentation strips for use at recorders. These strips contain provisions for three signal inputs to the computer.

- Power supplies.

- Dynamic inputs (an oscillator input) to the fuel valve and bleed control circuits and a step to the bleed control circuits.

Cabling

The system requires a 115 volts 60 cps input line to the EK15 power supply. This line is unfused to an output to the EK14 assembly and to three utility receptacles for auxiliary test components such as meters and oscillators. The line is fused to the D. C. voltage power supplies which consist of ±5, ±15 and a variable 0 to 34 VDC. The several cables used with the system are listed here:

- Interrack
    - AC power to EK14
    - ±15 VDC to EK14
    - ±15 and ±5 (one cable) to EK15 card chassis
    - Voltmeter connection
- Engine
    - One multiple cable between the EK14 chassis and the fuel control, pressure ratio sensor, pressure sensor, and pulse pickup
    - Two cables between the EK15 card chassis and a burner pressure sensor and a differential pressure sensor

- One multiple cable between the EK15 chassis and the bleed control servo and the bleed position transducer.

- One coaxial cable, the use of which is not defined

- Instrumentation

  One strip to the EK14 and two strips to the EK15 card chassis

- Trim Signals

  Two fanning strips attached to one connector at the EK14 chassis and two fanning strips attached to two connectors at the EK15 card chassis.

  Instrumentation inputs are included in trim Cable #2.

- Digital Words

  One word for engine speed from the EK14 chassis and two words from the EK15 card chassis

- Variable Signals

  Four signals from the EK14 chassis through the same connector as the trims and eight signals from the EK15 chassis

- Pace Computer

  One cable to the EK15 card chassis with a jumper cable to the EK14 chassis.

- Voltage to Frequency Converter

  One cable from the EK15 card chassis to a converter which has a frequency input cable for attachment to the various frequency inputs

- Oscillator Input

  One cable for fuel valve oscillator input to the EK14 fuel control circuit and one cable to the EK15 position control circuits.

Chassis Features

Figure 34 shows the EK14 chassis arrangement. Position of the various circuit cards are shown. Figure 35 shows the EK15 card chassis. Details of the cards are discussed in sections describing the circuits.

The EK14 chassis contains a digital voltmeter which is used for monitoring signals from both chassis. Adjustment values are read by the voltmeter by placing selection switches in appropriate positions. Voltmeter attachment sockets on the EK15 are shown.

Circuit selection switches are shown by Figure 35. These fourteen switches are incorporated to provide some flexibility. Switches 1, 2, and 3 have no attachments. Switches 4, 5, 6 and 7 are used to select inputs to the four position control circuits. A step in position request can be made by setting the step size by potentiometer adjustment 16 and switching 8 on and off. Oscillator input to the position circuits is accomplished through the banana plug sockets noted. Switches 9 and 10 are used to switch trims 10 through 15 from the trim input fanning strip to unused pressure and position circuits for direct input to the computer terminal.

Switches 11 and 12 are used to switch the two DAC signals to various position circuits as noted. Switch 12 is set to the off position.

Switches 13 and 14 are used to change the effective voltage range of the adjustment potentiometers from -5 VDC to zero to -5 VDC to +5 VDC. The switches are set to the zero (common) position.

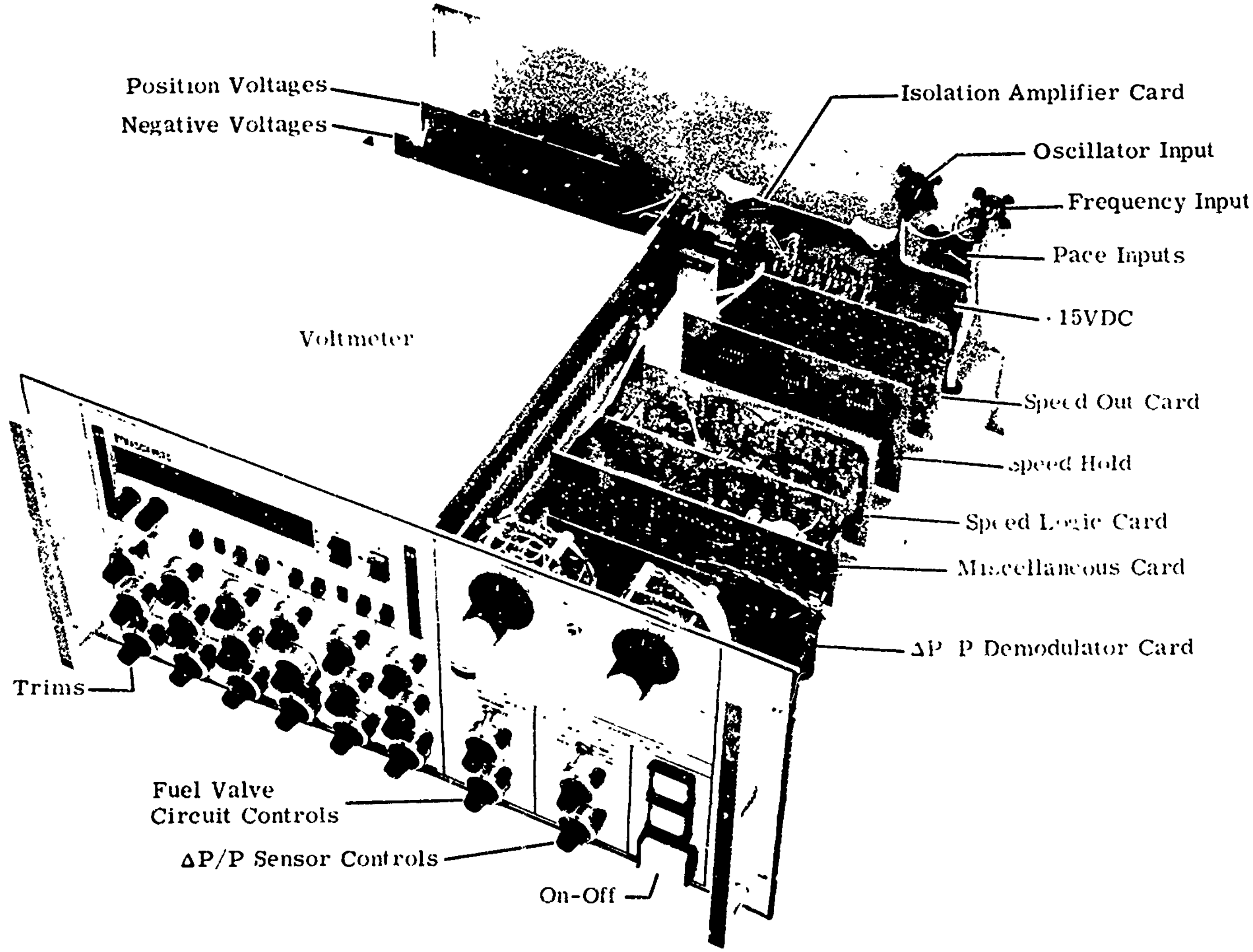


Figure 34 -- EK 14 Chassis

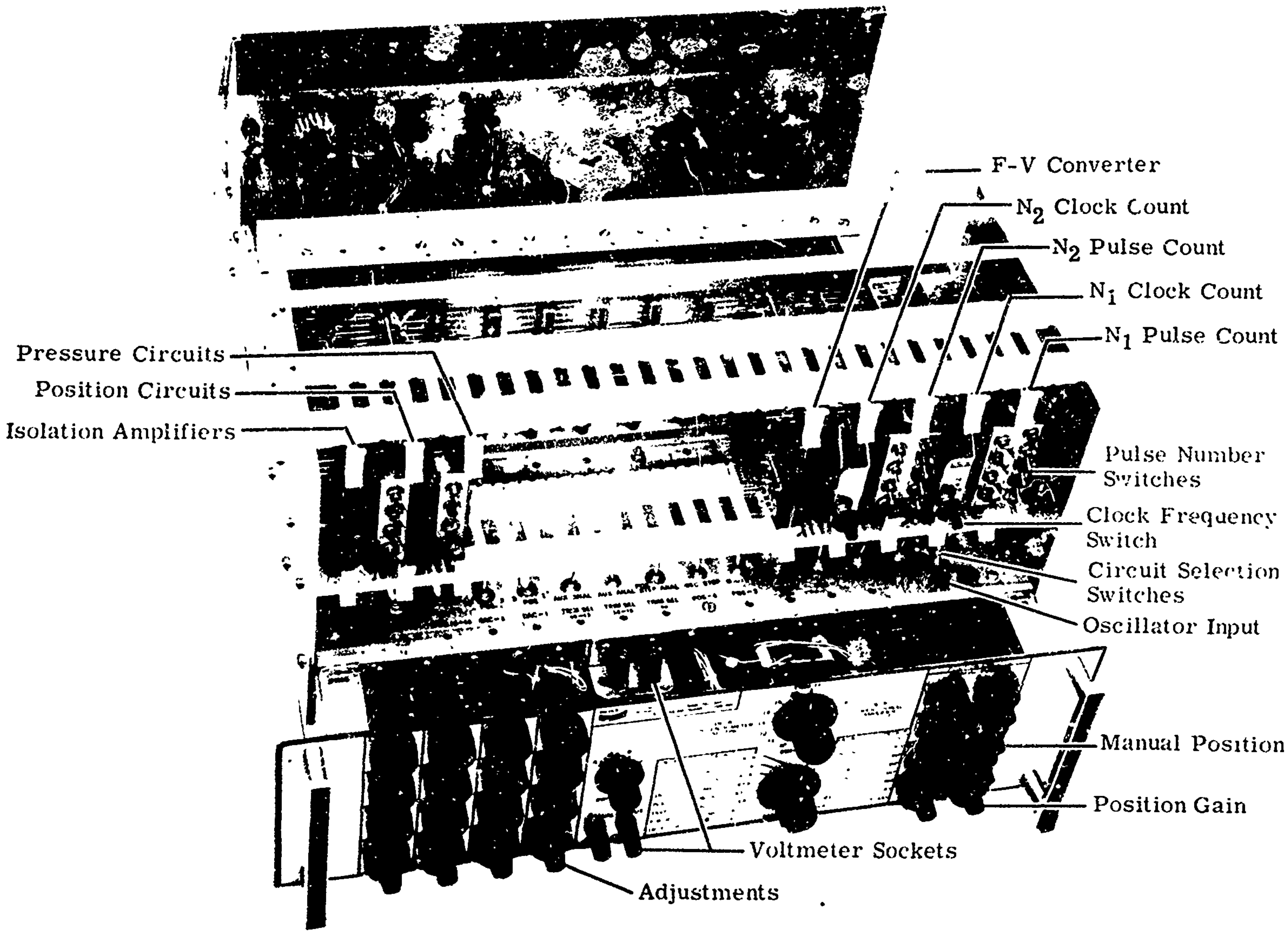


Figure 35 -- EK15 Card Chassis

IBM 1800 PROGRAM ADJUSTMENTS

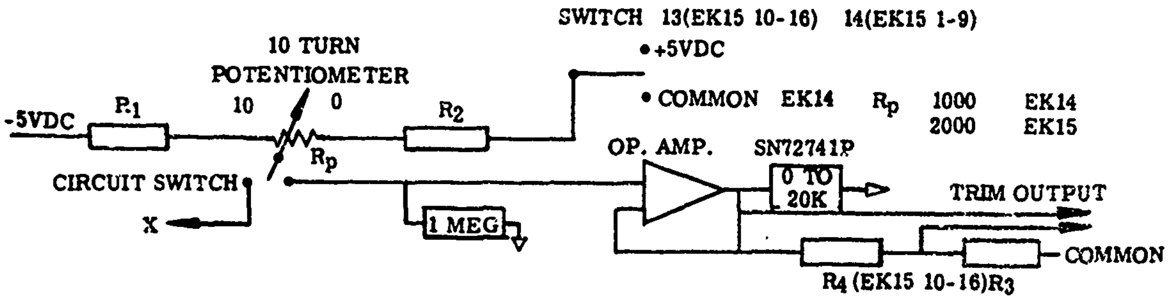
Thirty-four (34) ten-turn potentiometer adjustments are included for ease of changing the constants of the computer program. Eighteen of these adjustments were included in EK-14. These adjustments have limited voltage range. Sixteen adjustments are included in EK15 card chassis. Nine of these adjustments are full range voltage including a selection between -5 VDC to +5 VDC or to common. The primary purpose of these adjustments is for schedules of engine geometry control. The change from positive to negative voltage is for change of slope through zero if required in the schedules. The other seven adjustments include the same voltage range as above but in addition have attenuation possibilities for low voltage input. Further, these adjustments are wired through switches for other circuit uses or computer input through unused pressure or position circuits as may be desired for program additions.

Each adjustment output is through a Texas Instrument SN72741P operational amplifier. The trim circuits are illustrated by Figure 36. The circuit selector switches are located under the front edge of the Cambion card file.

Figure 37 is a photograph of the trim input fanning strips for mounting to the computer terminal. Trim number and name used in the IBM 1800 computer program are shown on the photograph. The trims from EK14 are from one connector on the package, while two connectors are used for the EK15 trims. Undefined signals which might be useful in engine operation can be input to the computer through the two instrumentation inputs.

Figure 38 is a photograph of the EK14 Cambion card containing the isolation amplifiers for the trim circuits. Isolation amplifiers for analog signals are also included on the card. In addition circuits for pace computer inputs are provided as noted by card inputs of Figure 38.

Figure 39 is a photograph of the EK15 trim isolation amplifier card. This card also includes two isolation amplifiers for instrumentation strip signals. Also an isolation amplifier is incorporated for use of the Dac #2 variable at the instrumentation strip. Inputs of Trims 10 through 16 can be through resistors to obtain low voltage outputs. These resistors are mounted on a socket strip and can be included in the circuit by replacing the wire on a strip used to obtain high voltage output.



EK14 TRIM	R_1	R_2	R_3	R_4	CIRCUIT SWITCH	X
1	500	0	None	0 Wire	None	
2	00	0				
3	0	0				
4	0	0				
5	0	500				
6	0	250				
7	0	0				
8	0	250				
9	1000	0				
10	0	0				
11	1000	0				
12	1000	0				
13	1000	0				
14	0	0				
15	0	0				
16	500	500				
17	500	500				
18	500	0	None	0 Wire	None	
EK15 TRIM						
1 THRU 9	None	None	None	0 Wire	None	
10	None	None	33200 or 332	Wire or 33.2K	10	P3
11					10	P4
12					10	NONE
13					10	NONE
14					9	Pos. 3
15					9	Pos. 4
16					8	Step Input

Figure 36 -- Trim Circuits

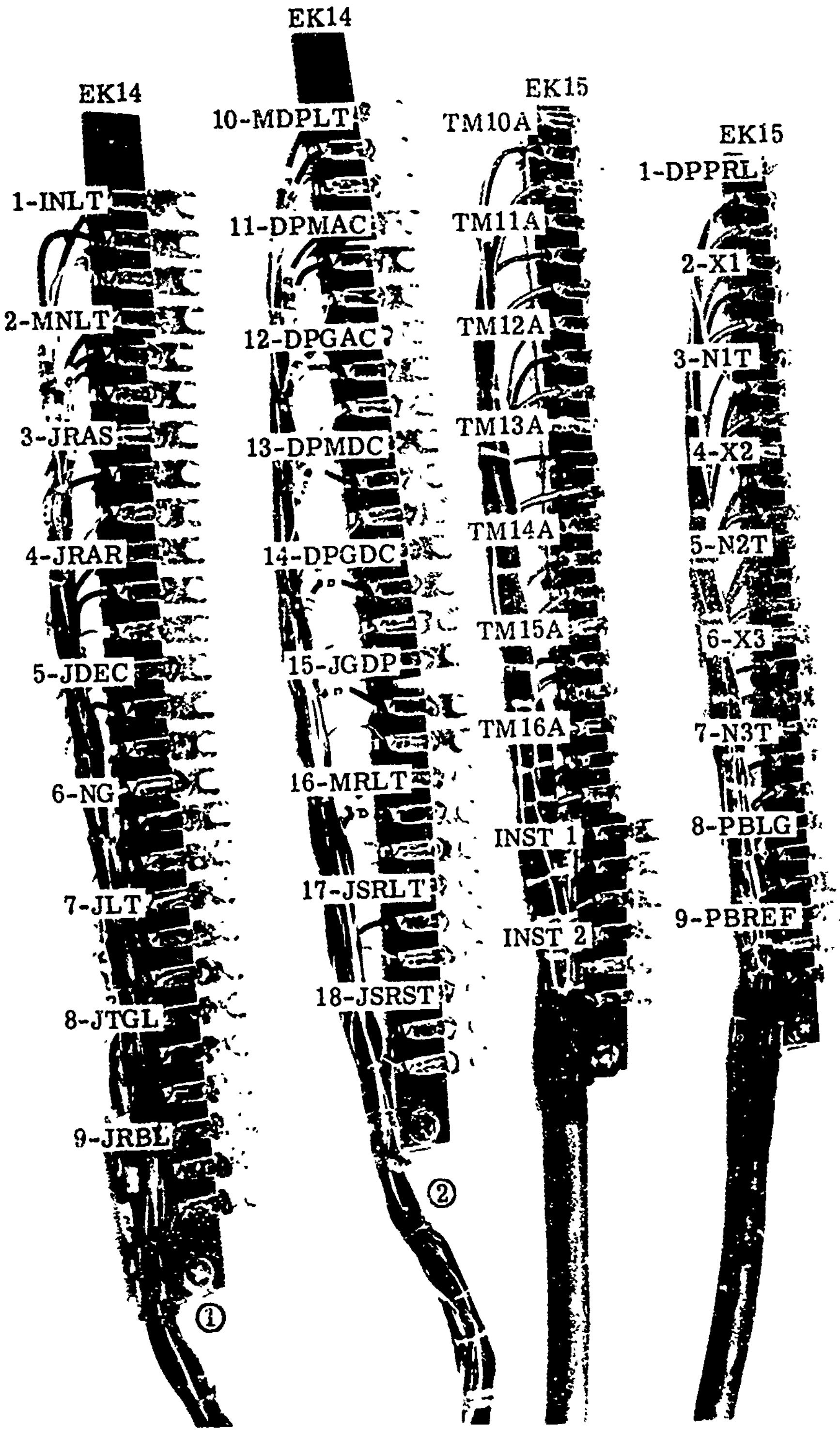
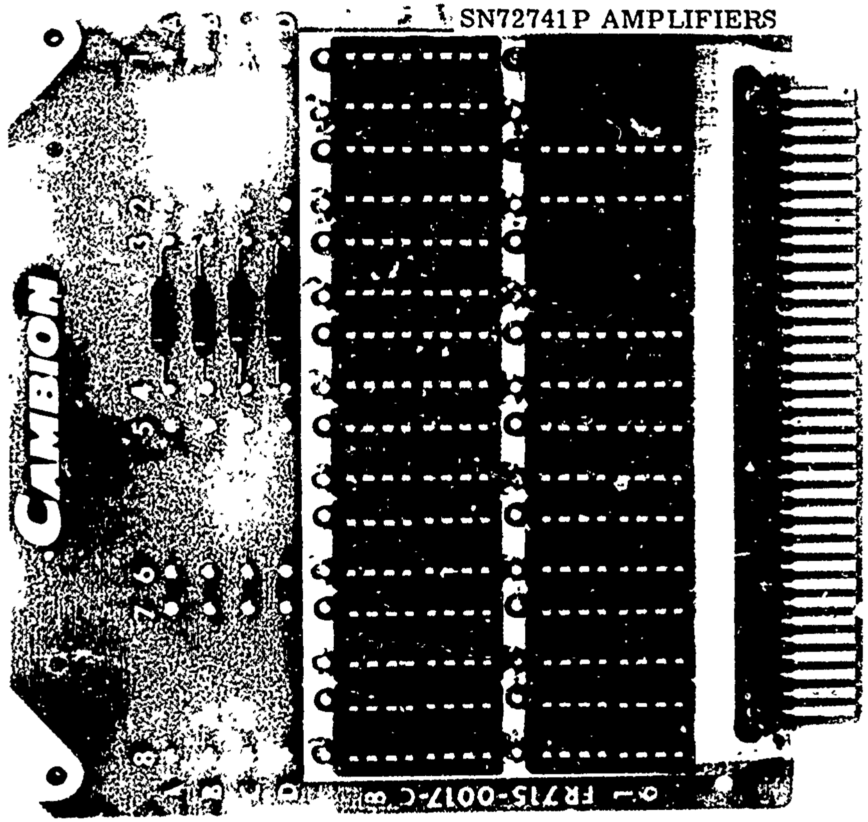
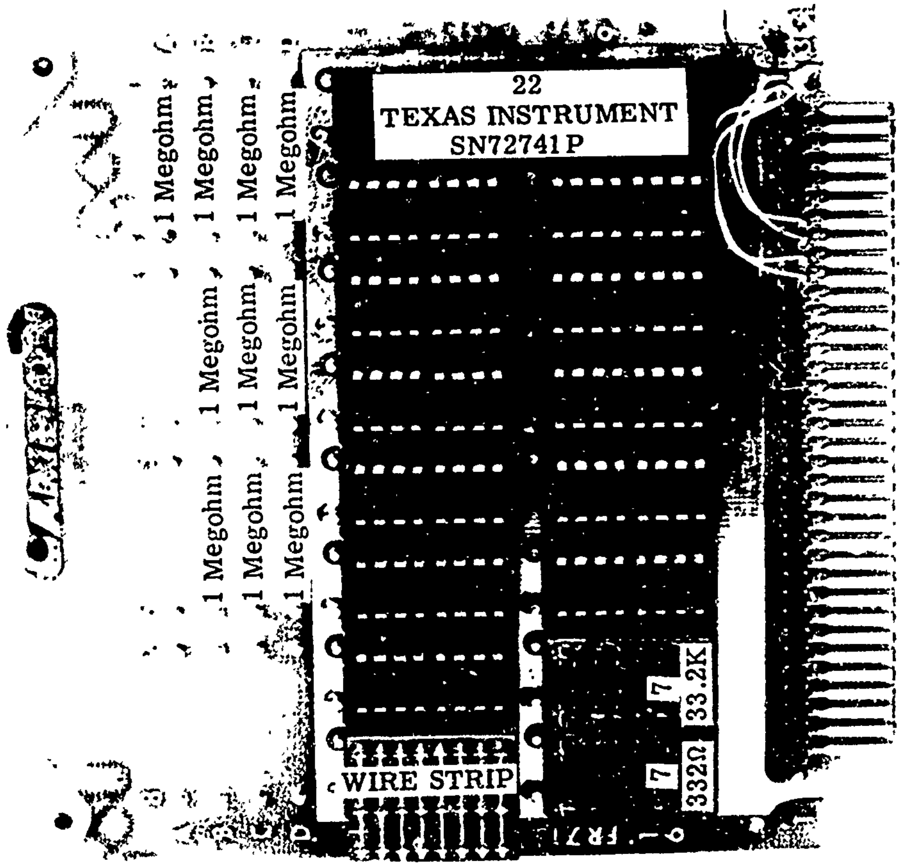


Figure 37 -- Photograph of Trim Fanning Strips



COMPONENT SIDE				PIN SIDE
35		COMMON		70
34		COMMON		69
33		+ 5VDC		68
32		+ 5VDC		67
31		- 5VDC		66
30		- 5VDC		65
29		-15VDC		64
28		-15VDC		63
27		+15VDC		62
26		+15VDC		61
25	TRIM 14-SW9		TRIM 15-SW9	60
24	DYN SW5-20K		DYN-SW7 20K	59
23	DYN SW4-20K		DYN-SW6-20K	58
22	POS F B 4		POS 4 COMPUTER	57
21	GAIN 4		POS 4 INST	56
20	TM 4		TM 4	55
19	DAC 2 SW12		POS REQ INST	54
18	POS F B 3		TM CURRENT	53
17	POS F B 3		POS 3 COMPUTER	52
16	GAIN 3		POS 3 INST	51
15	TM 3		TM 3	50
14	DAC 2 SW12		POS REQ. INST.	49
13	MAN POS 3		TM CURRENT	48
12	POS F B 2		POS 2 COMPUTER	47
11	GAIN 2		POS 2 INST	46
10	TM 2		TM 2	45
9	DAC 1 SW11		POS REQ INST	44
8	MAN POS 2		TM CURRENT	43
7	POS F B 1		POS 1 COMPUTER	42
6	GAIN 1		POS 1 INST	41
5	TM 1		TM 1	40
4	DAC 1 SW11		POS REQ. INST	39
3	MAN POS 1		TM CURRENT	38
2		COMMON		37
1		COMMON		36

Figure 38 -- EK14 Isolation Amplifier Card



COMPONENT SIDE			PIN SIDE	
35		COMMON		70
34		COMMON		69
33		+ 5VDC		68
32		+ 5VDC		67
31		- 5VDC		66
30		- 5VDC		65
29		-15VDC		64
28		-15VDC		63
27		+15VDC		62
26		+15VDC		61
25	INPUT TRIM 1		OUTPUT TRIM 1	60
24	2		2	59
23	3		3	58
22	4		4	57
21	5		5	56
20	6		6	55
19	7		7	54
18	8		8	53
17	9		9	52
16	10		10	51
15	11		11	50
14	12		12	49
13	13		13	48
12	14		14	47
11	15		15	46
10	INPUT TRIM 16		OUTPUT TRIM 16	45
9	INPUT INST. 1		OUTPUT INST. 1	44
8	INPUT INST. 2			43
7			OUTPUT INST. 2	42
6				41
5	INPUT DAC #2		OUTPUT DAC #2	40
4				39
3				38
2		COMMON		37
1		COMMON		36

Figure 39 -- Trim Isolation Amplifier Card

ENGINE CONTROL VARIABLES

Variable inputs to the IBM 1800 Computer terminal consist of:

	NAME	SYMBOL	COMPUTER NAME
1.	Power lever	PLA	JPLA
2.	Fuel valve position (instrumentation)	Wf	Not assigned
3.	Burner pressure	P3	JPB
4.	Burner pressure	PB	RPB
5.	Differential pressure	ΔP	DP
6.	Pressure ratio	$\Delta P/P$	BJDP
7.	Pressure circuit	P3	Not assigned
8.	Pressure circuit	P4	Not assigned
9.	Bleed valve position	POS 1	Not programmed
10.	Position circuit	POS 2	Not assigned
11.	Position circuit	POS 3	Not assigned
12.	Position circuit	POS 4	Not assigned
13.	EK14 instrumentation strip, T	T4	JT4
14.	EK15 instrumentation strip #1	INST 1	Not assigned
15.	EK15 instrumentation strip #2	INST 2	Not assigned

The circuits P3, P4, POS 3, and POS 4 contain inputs from EK15 Trims 10, 11, 14, 15 respectively and may be used with those trims for program adjustment if needed. EK 15 instrumentation strip inputs are included on trim cable #2.

Figure 40 shows the fanning strip arrangement for control signals. Also the inputs for the three computer digital-analog converter outputs (DACO, DAC1, and DAC2) are shown. These outputs are JWF, fuel valve position request, used for the variable equal to differential pressure (ΔP) divided by burner pressure PB.

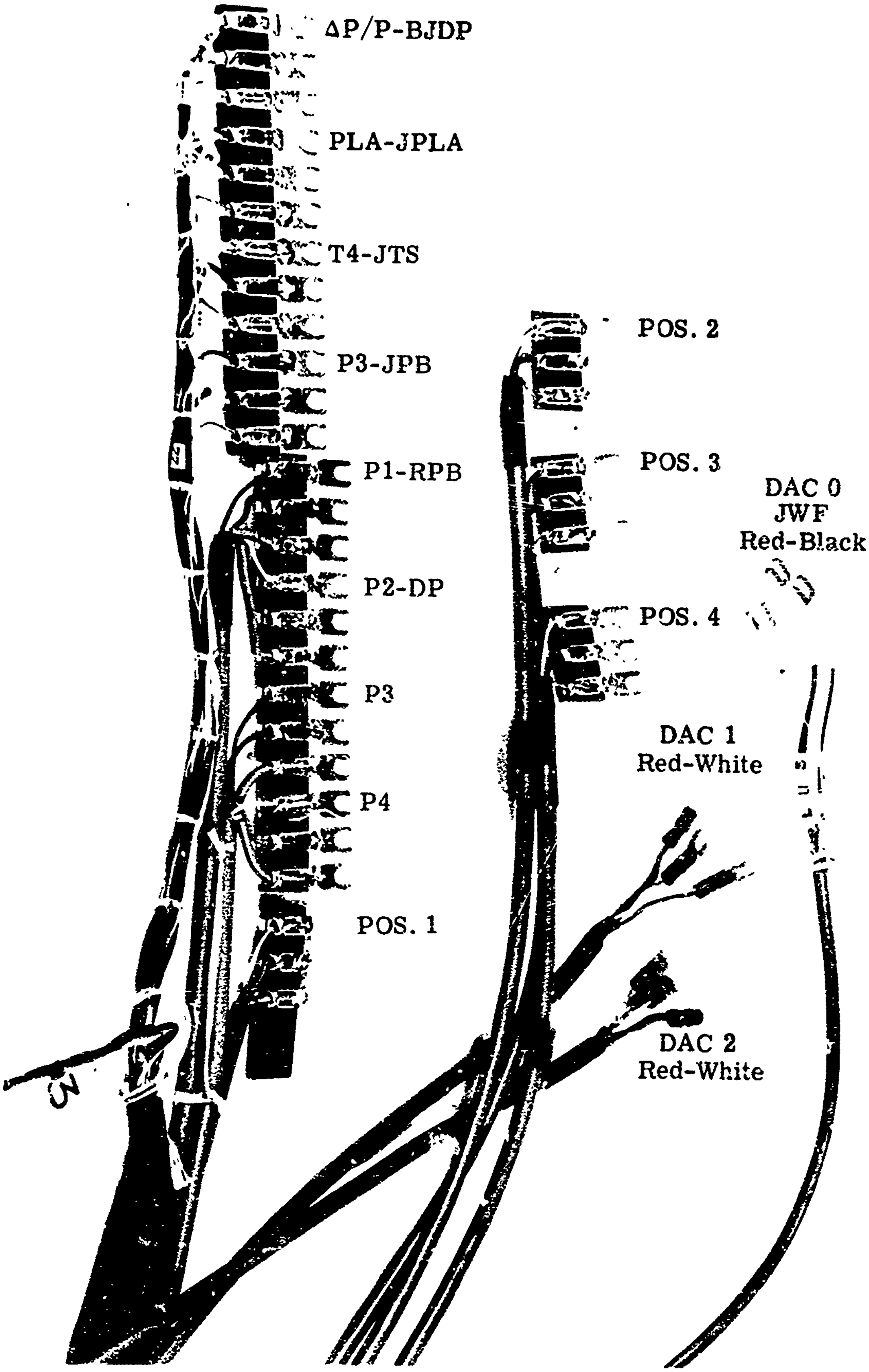


Figure 40 -- Engine Control Variable Fanning Strip

The EK14 variable cable is included in a bundle along with the EK14 trim circuits. The isolation amplifiers for these signals are shown by Figure 78 . The EK15 variable is from a connector separate from the EK15 trims.

The control system variables are obtained through engine mounted components including:

- One fuel control valve assembly, Model EH-G1 with power lever potentiometer and cutoff valve;
- One pressure ratio sensor, Model PRA-A1;

  Two pressure sensors, CEC 4-326-0001;
- One, pressure sensor, CEC-4-312-0002;
- One, electromagnetic pulse generator for speed pickup (engine parts list);
- One, bleed position control servo valve (Moog Series 73), and
- One, bleed position feedback potentiometer Bourns 2001782009.

Connections to these components are through cables listed on page 91.

The various conditioning circuits are contained on two printed circuit boards in the EK14 chassis and two Cambion wire wrap cards in the EK15 chassis.

Figure 41 through 43 illustrate the EK14 circuits. Figure 41 is the wiring schematic of the $\Delta P/P$ sensor demodulator and Figure 42 is a photograph of the demodulator printed circuit card. Figure 43 is a wiring schematic of the miscellaneous card including the burner pressure sensor, the fuel control valve driver amplifier and an analog speed frequency to voltage converter. Figure 44 is a photograph of the miscellaneous printed circuit card.

Figure 45 is a schematic of the pressure sensing circuits of the EK15 card chassis. The outputs from each of the four pressure circuits is through isolation amplifiers to both the instrumentation strip and to the computer terminal. Each output can be selected by the "B" switch to monitor the output on the package voltmeter. Circuits 1 and 2 contain provisions for input from the Pace checkout computer. Since circuits 3 and 4 are not used in the initial programming, provisions are incorporated to use trims 10 and 11 through these inputs to the computer program.

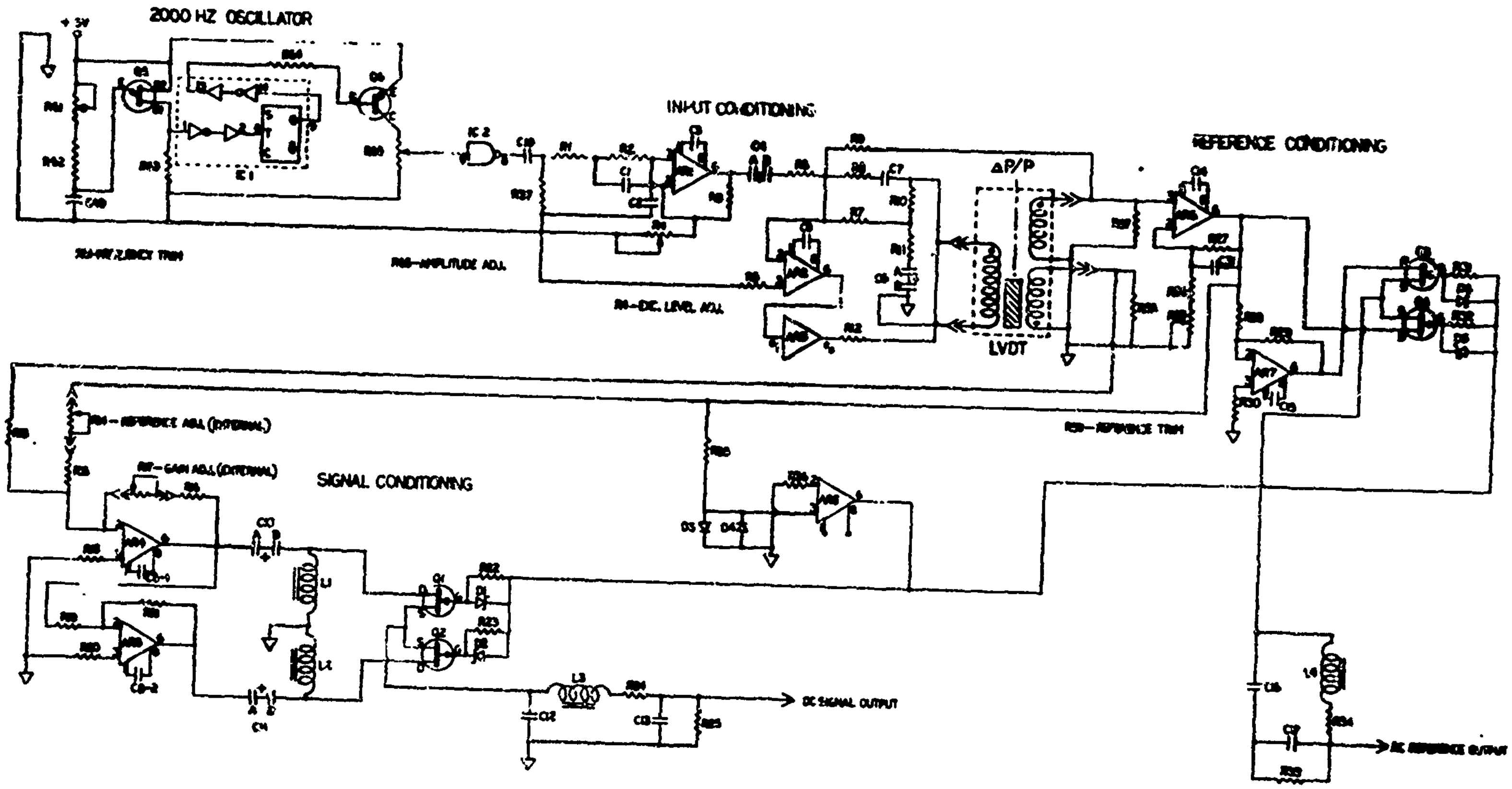


Figure 41 Pressure Ratio Sensor Demodulator

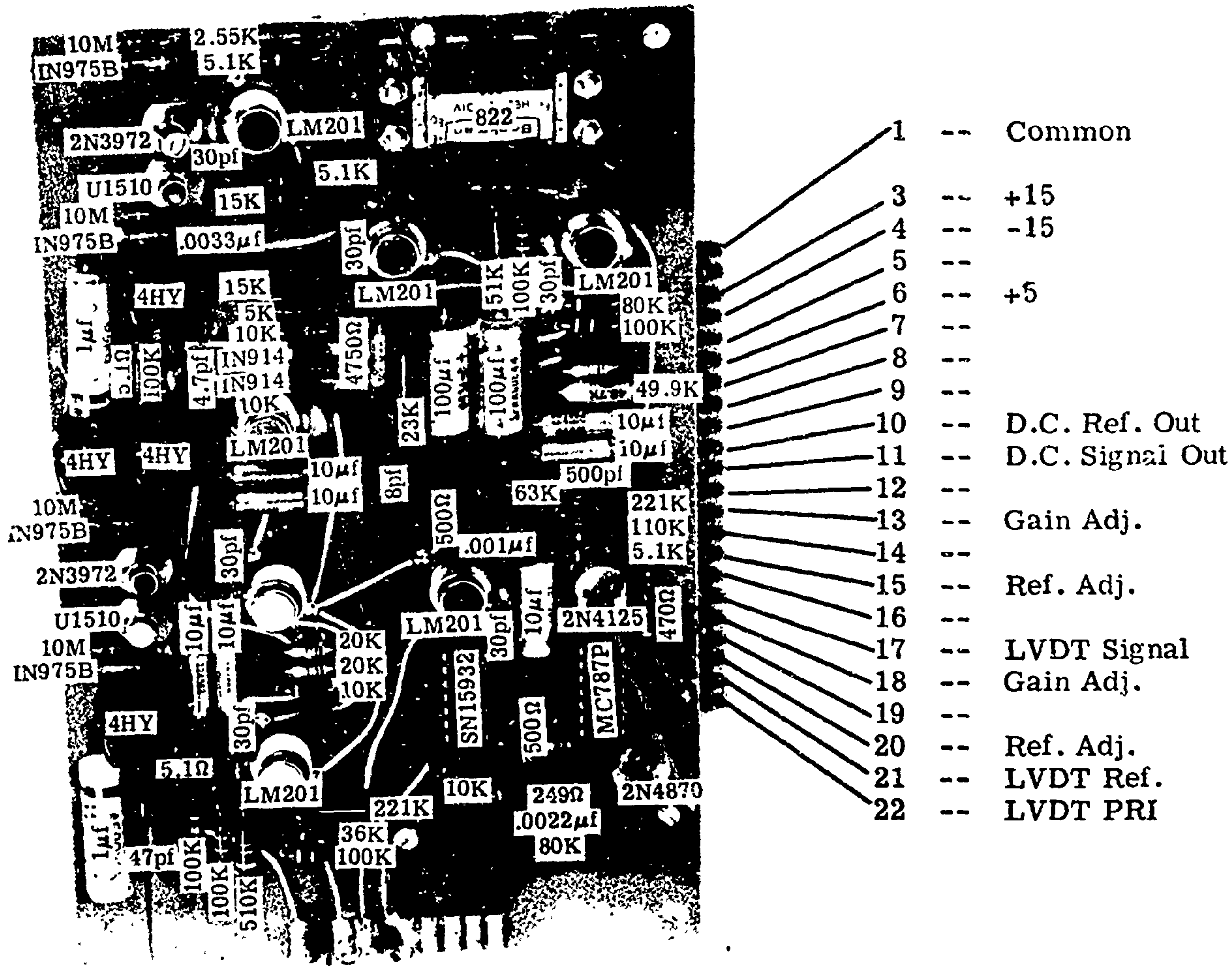
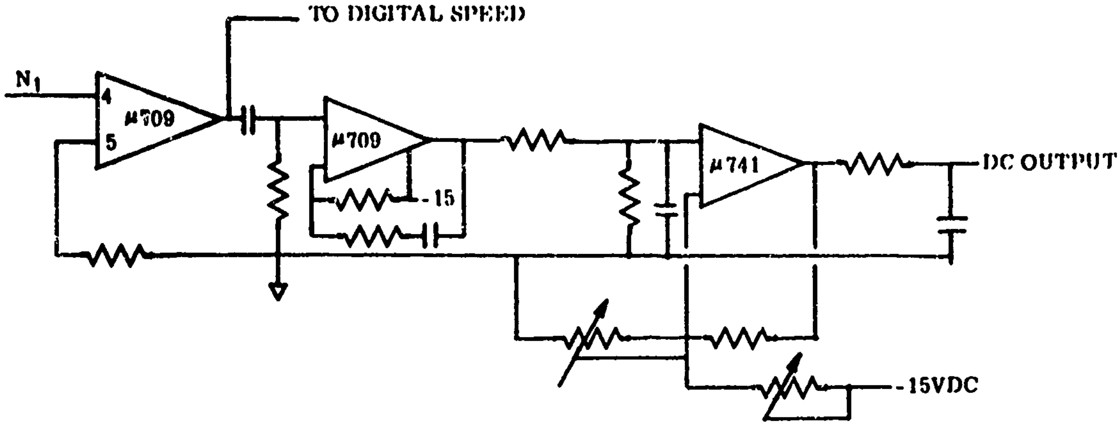
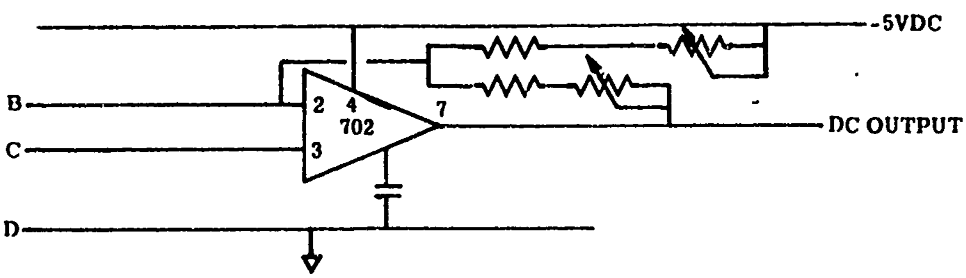


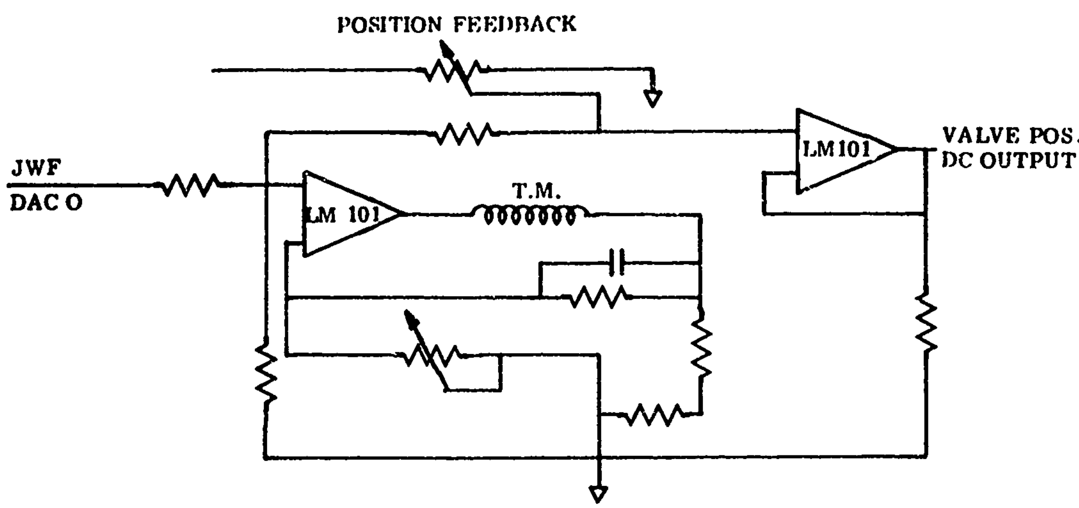
Figure 42 -- Demodulator Printed Circuit Card



ANALOG SPEED SIGNAL



PRESSURE SENSOR CIRCUIT



TORQUE MOTOR DRIVER CIRCUIT

Figure 43 -- Miscellaneous Circuits Schematic

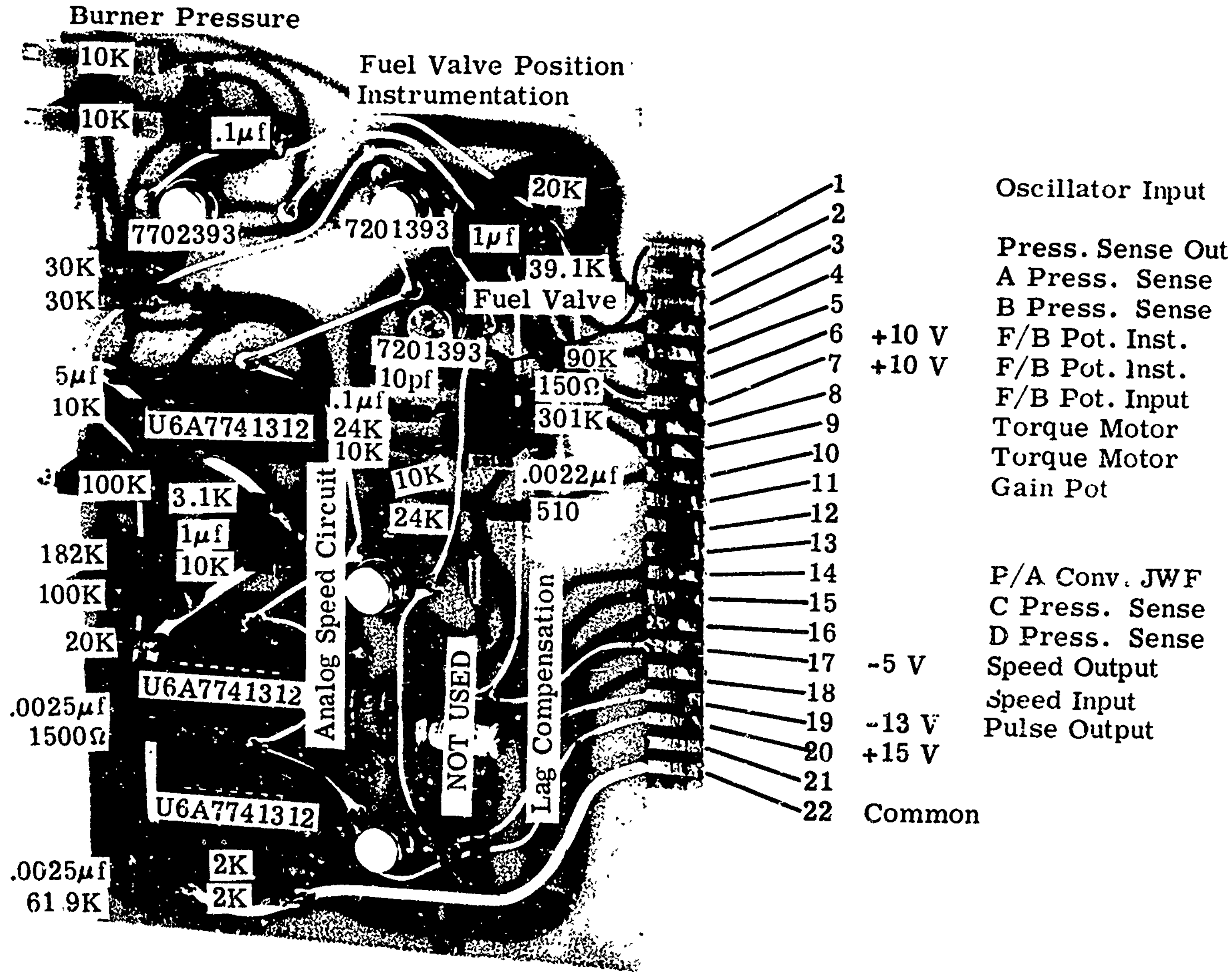


Figure 44 — Miscellaneous Printed Circuit Card

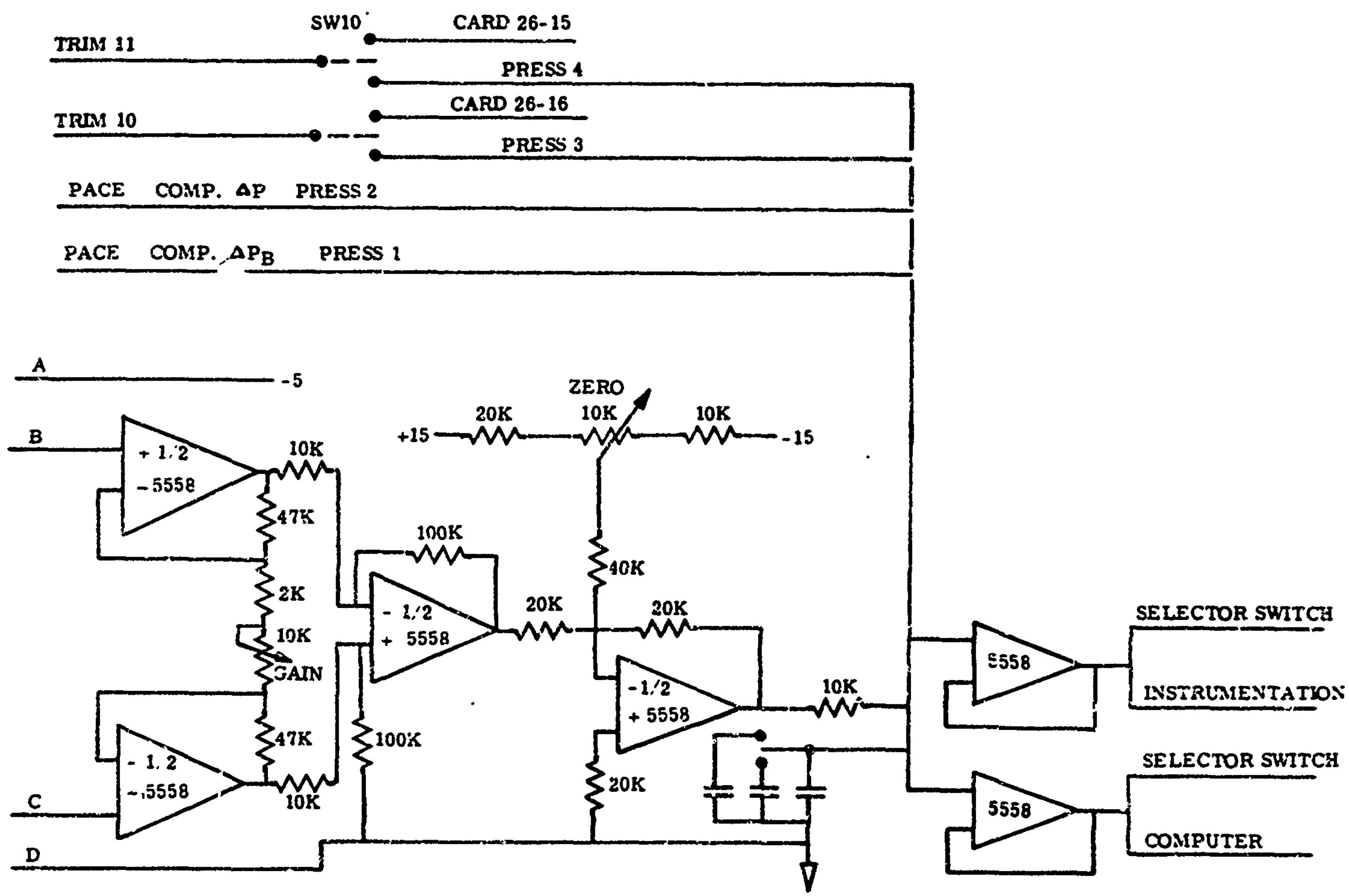
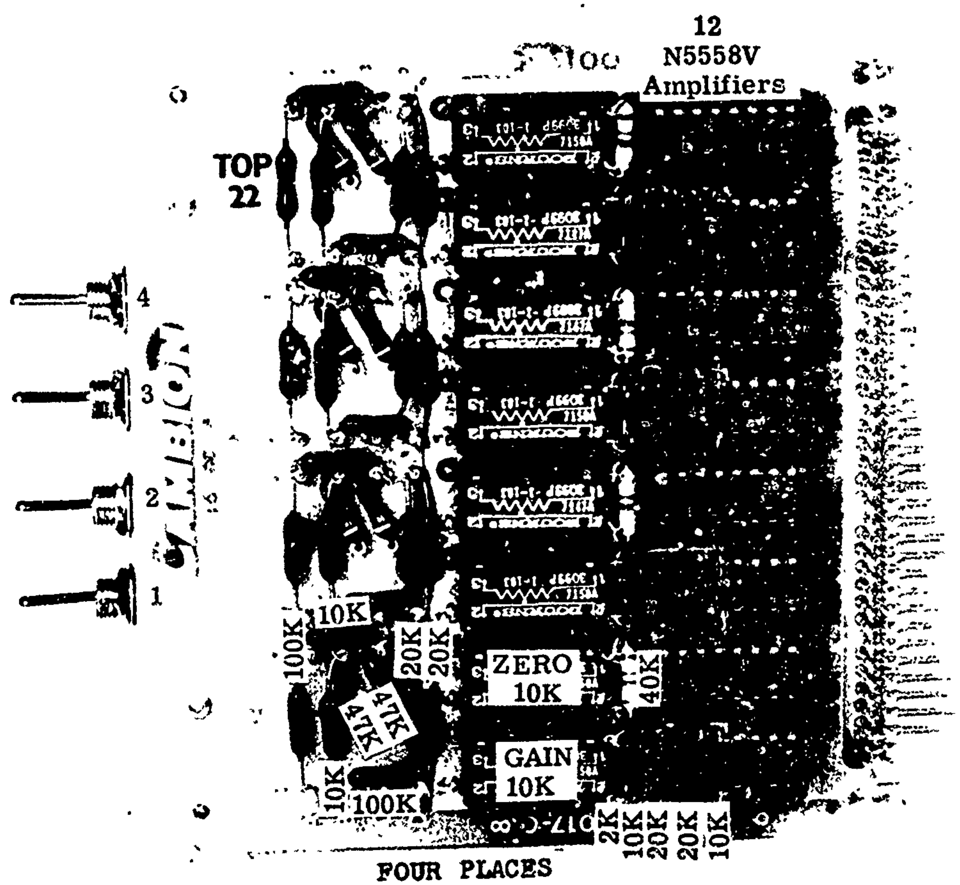


Figure 45 -- Schematic of Pressure Sensing Circuits



COMPONENT SIDE				PIN SIDE
35		COMMON		70
34		COMMON		69
33		+ 5VDC		68
32		+ 5VDC		67
31		- 5VDC		66
30		- 5VDC		65
29		-15VDC		64
28		-15VDC		63
27		+15VDC		62
26		+15VDC		61
25				60
24				59
23			COMP-P4	58
22	P4			57
21	TRIM 11		INSP-P4	56
20	P4			55
19				54
18			COMP-P3	53
17	P3			52
16	TRIM 10		INST-P3	51
15	P3			50
14				49
13	ΔP PACE		COMP-P2	48
12	P2			47
11			INST-P2	46
10	P2			45
9				44
8	PB PACE		COMP P1	43
7	P1			42
6			INST-P1	41
5	P1			40
4				39
3				38
2		COMMON		37
1		COMMON		36

Figure 46 -- Pressure Circuit Card

Figure 46 is a photograph of the pressure circuit card. The switches on the card are used to select output filtering capacitors.

Figure 47 is a schematic of the position control circuits of the EK15 card chassis. Each of the four circuit outputs to the computer terminal and to the instrumentation strip is through isolation amplifiers. The two DAC signals from the computer can be used for position request inputs as shown. Since circuits 3 and 4 are not used for this program, provisions to use Trims 14 and 15 through the circuits are incorporated. Each circuit contains a switch on the card for either manual or DAC input. Each circuit has provisions for dynamic input either by step using Trim 16 or by an oscillator input. The potentiometers for gain adjustment and manual position request are located on the front of the chassis. Figure 48 is a photograph of the position circuit card.

Figure 49 is a block diagram of the frequency to voltage converter incorporated in the EK15 card chassis. These two circuits are used to generate voltage signals which may be used for instrumentation inputs to plotting boards or strip recorders. Figure 50 is a photograph of the Cambion card.

Figures 43 and 44 are the schematic and photograph of a similar frequency to voltage converter in the EK14 chassis used for engine speed monitoring and speed signal for data recording.

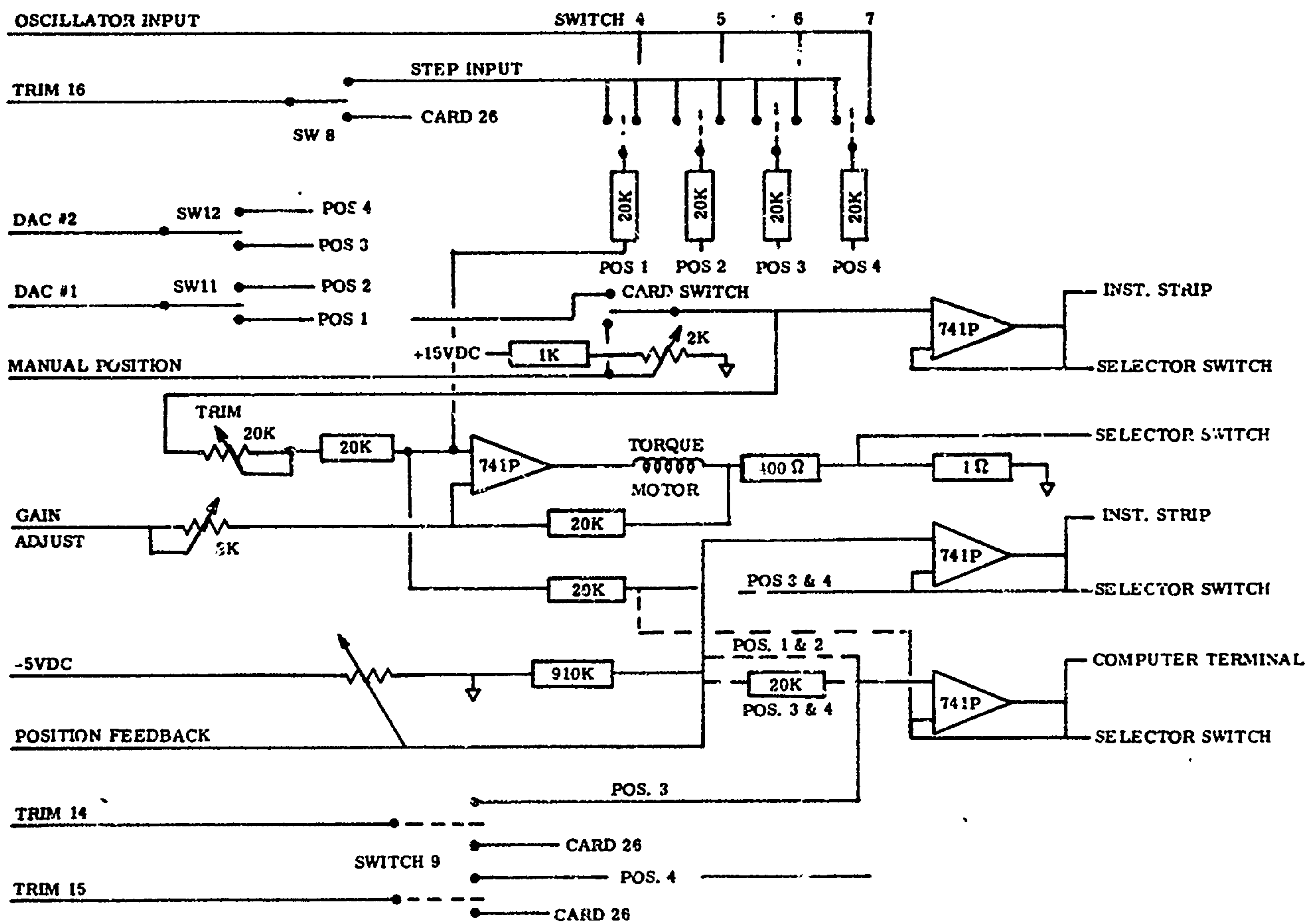
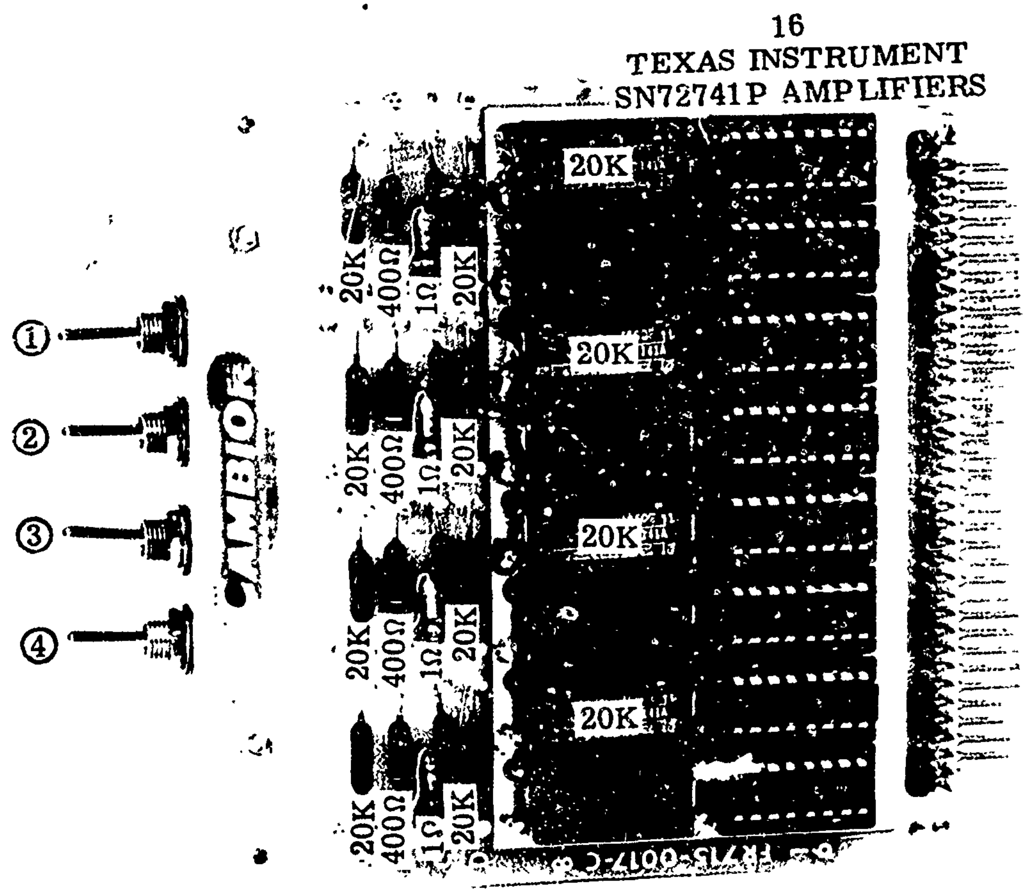


Figure 47 -- Schematic of Position Control Circuits



COMPONENT SIDE				PIN SIDE
35		COMMON		70
34		COMMON		69
33		+5VDC		68
32		+5VDC		67
31		-5VDC		66
30		-5VDC		65
29		-15VDC		64
28		-15VDC		63
27		+15VDC		62
26		+15VDC		61
25	TRIM 14 SW9		TRIM 15-SW9	60
24	DYN SW5-20K		DYN SW7 20K	59
23	DYN SW3 20K		DYN-SW6-20K	58
22	POS F B 4		POS 4 COMPUTER	57
21	GAIN 4		POS 4 INST	56
20	TM 4		TM 4	55
19	DAC #2 SW12		POS REQ INST	54
18	POS F B 3		TM CURRENT	53
17	POS F B 3		POS 3 COMPUTER	52
16	GAIN 3		POS 3 INST	51
15	TM 3		TM 3	50
14	DAC 2 SW12		POS REQ. INST.	49
13	MAN POS 3		TM CURRENT	48
12	POS F B 2		POS 2 COMPUTER	47
11	GAIN 2		POS 2 INST	46
10	TM 2		TM 2	45
9	DAC #1 SW11		POS REQ. INST.	44
8	MAN POS 2		TM CURRENT	43
7	POS F B1		POS 1 COMPUTER	42
6	GAIN 1		POS 1 INST.	41
5	TM 1		TM 1	40
4	DAC #1 SW11		POS REQ INST	39
3	MAN POS 1		TM CURRENT	38
2		COMMON		37
1		COMMON		36

Figure 48 -- Position Circuit Card

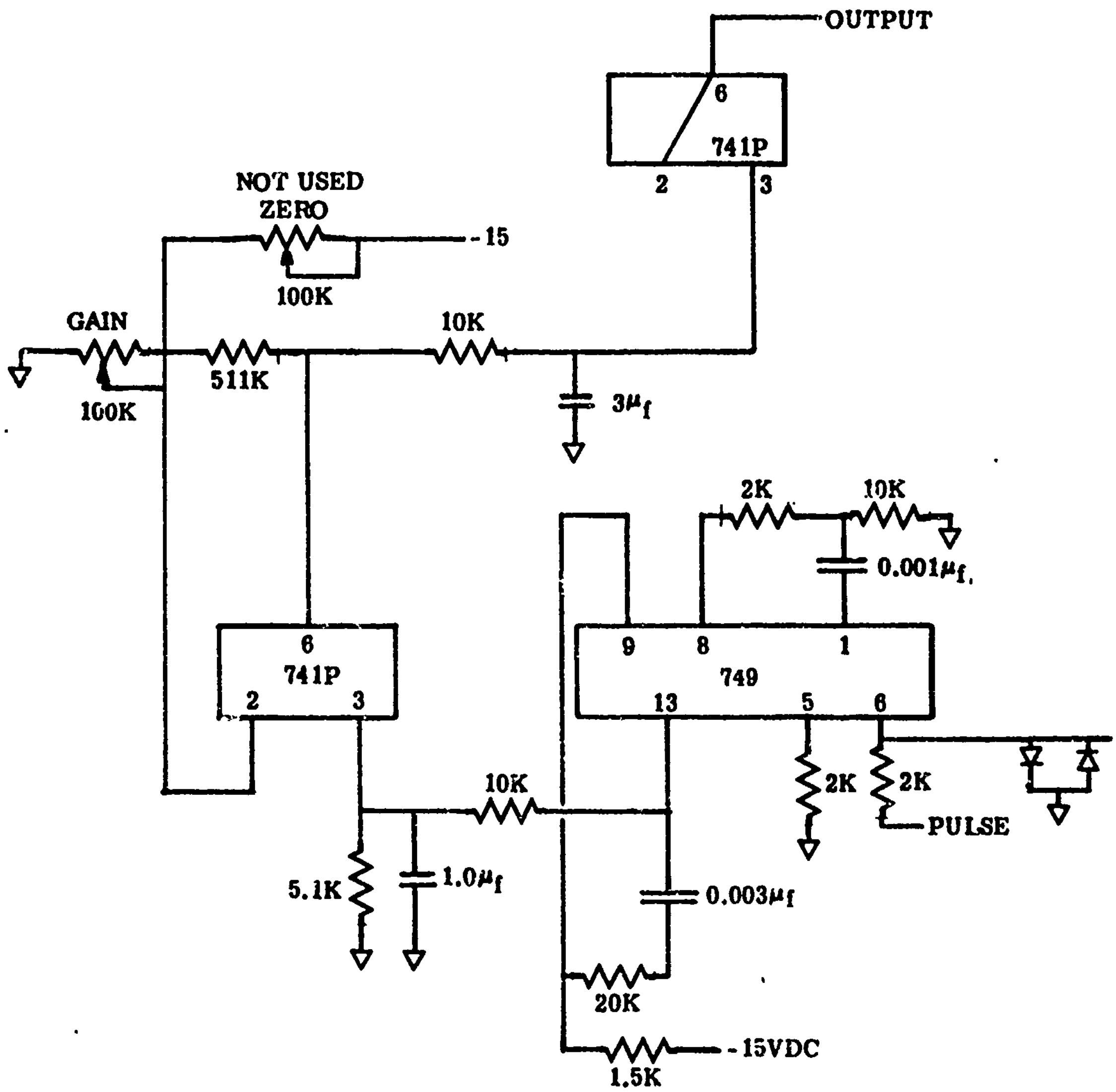


Figure 49 -- Frequency to DC Voltage Converter
(Analog Speed)

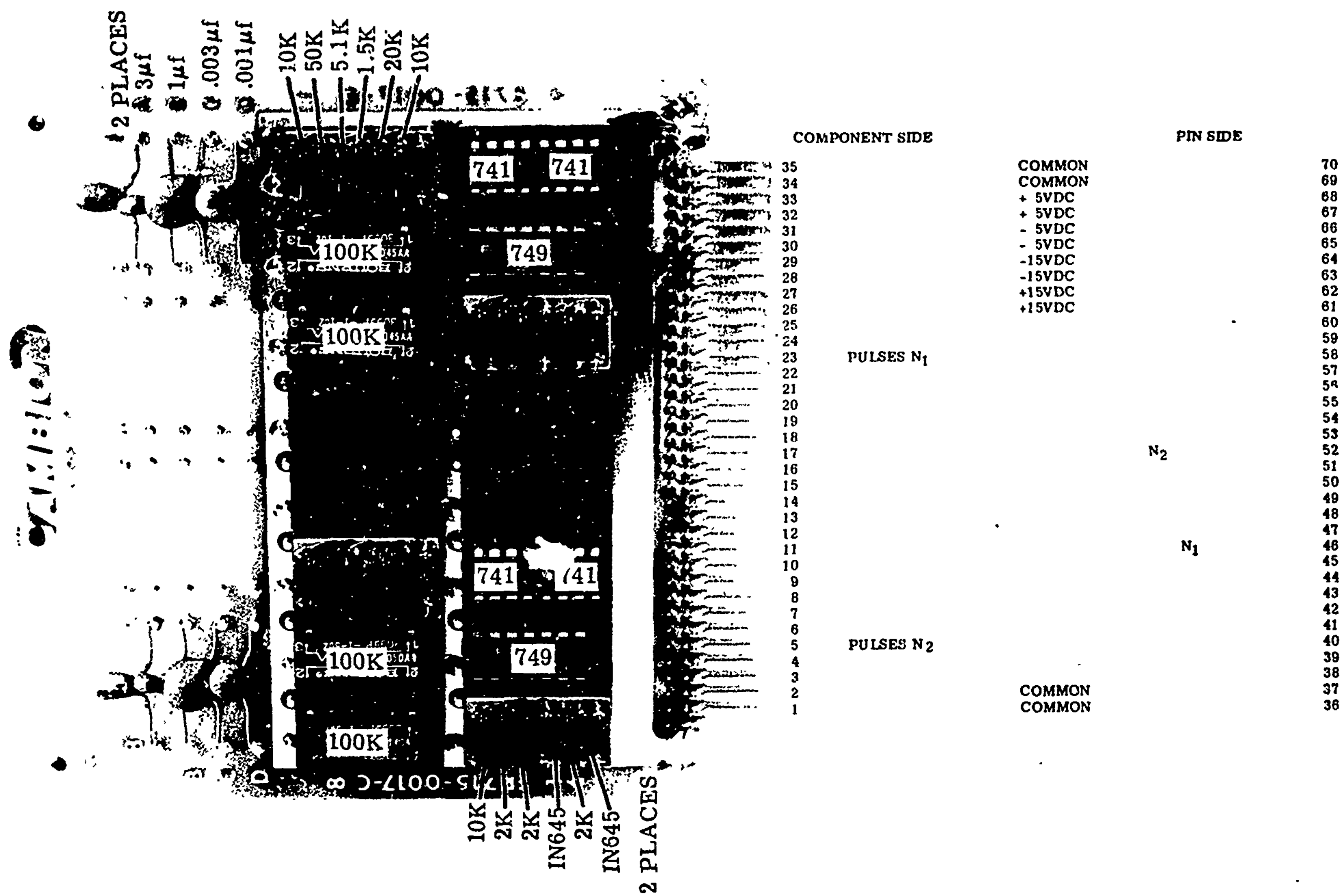


Figure 50 -- Frequency to DC Voltage Convertor Card

INSTRUMENTATION AND CHECKOUT CIRCUITS

Three (3) instrumentation strips are available to provide variable data for recording and monitoring equipment. Figures 51, 52, and 53 show the variables available at the barrier block terminals of these strips. There are available three points for input of variables on these strips. These inputs pass through isolation amplifiers in the interface and on to the computer terminals. Isolation amplifiers for the EK14 instrumentation strip are listed on Figure 38.

Several checkout circuits features are incorporated in the interface. The AFAPL Pace TR48 computer will be used for interface and IBM 1800 program checkout. The computer is programmed for engine simulation with outputs of speed, burner pressure, a differential pressure temperature, $\Delta P/P$, and power lever. Input to the Pace computer is fuel valve position request.

The speed signal is converted to a frequency by a commercial voltage to frequency converter. The signal to this circuit is from the EK15 chassis through cable. The frequency is input to the program through a MS3102A-10SL-3P connector in parallel with the normal speed pulse input.

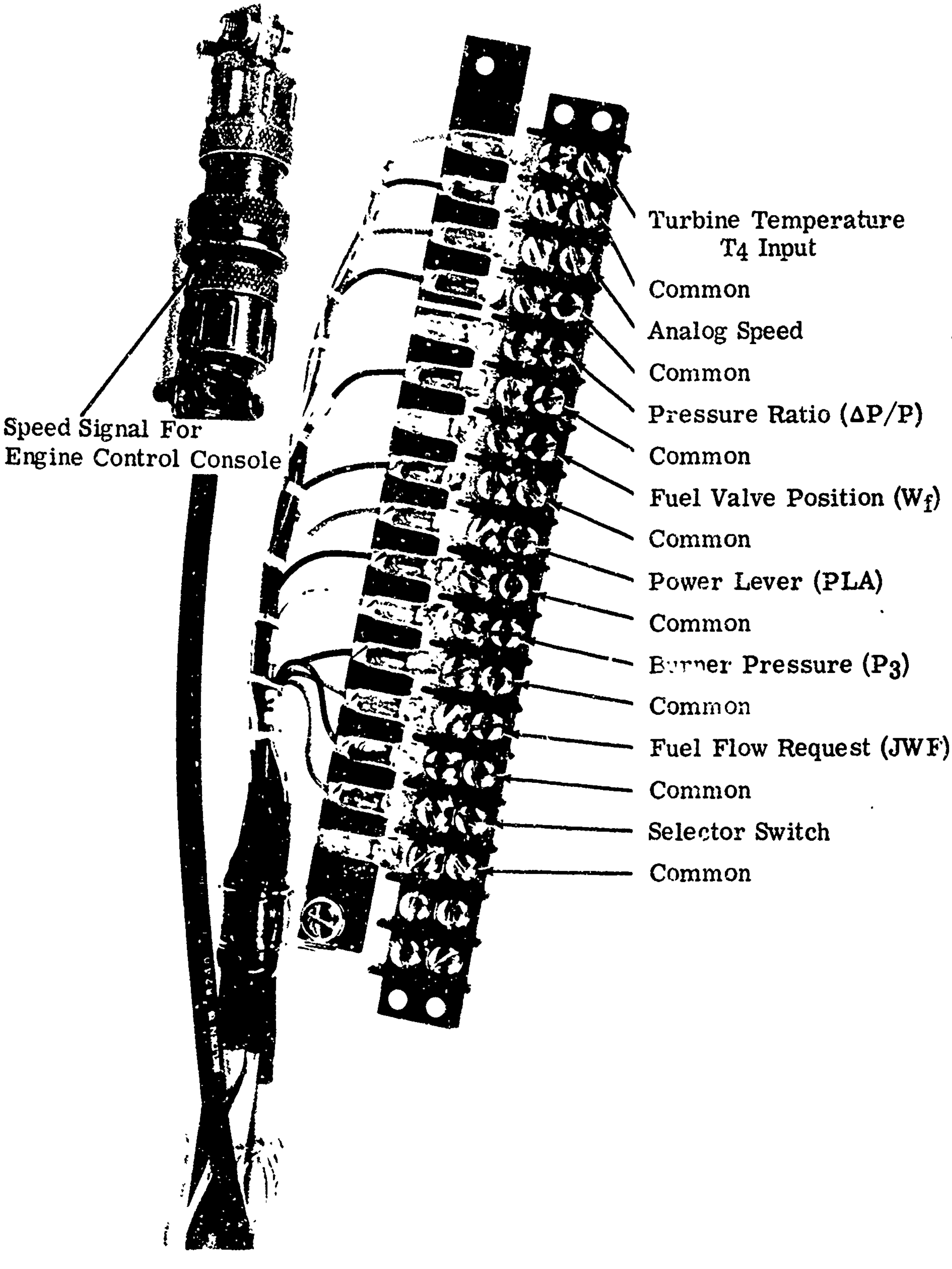


Figure 51 -- EK14 Instrumentation Strip

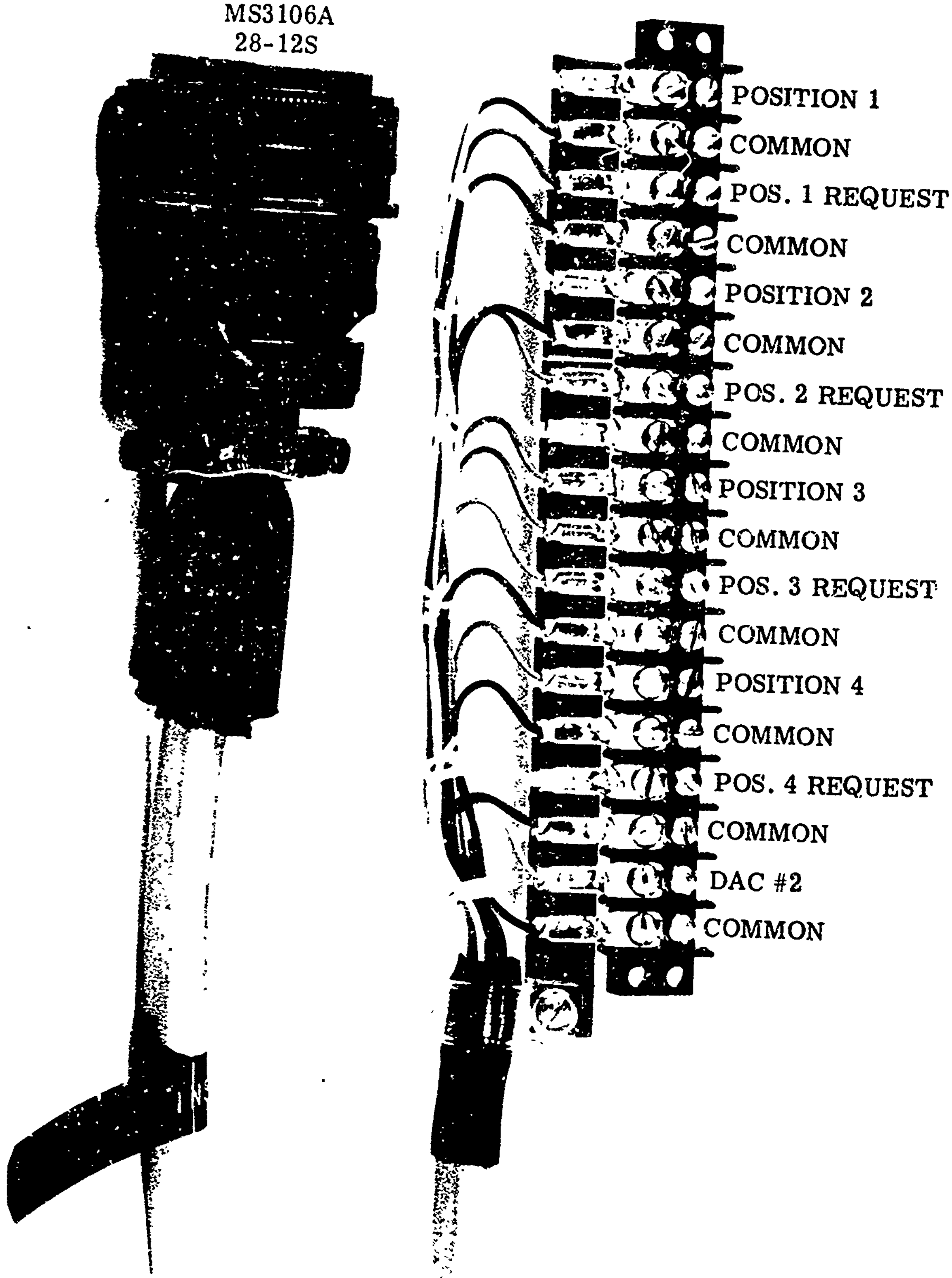


Figure 52 -- Instrumentation Strip No. 1

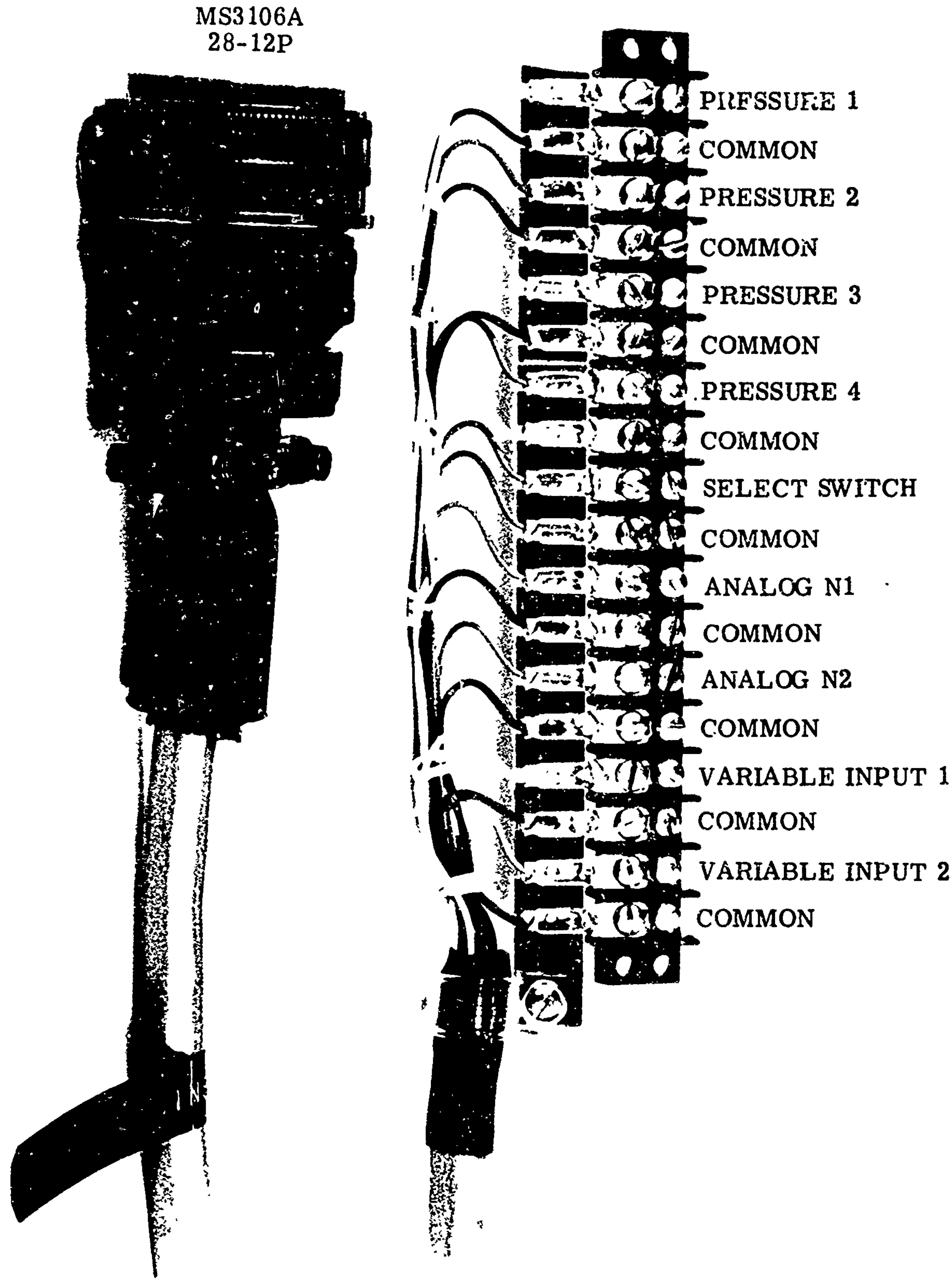


Figure 53 -- Instrumentation Strip No. 2

FREQUENCY TO DIGITAL WORD CONVERTERS

The package contains circuits for converting three frequency signals to digital words. The converter in the EK14 chassis was designed for engine speed input to the computer terminal. The two converters in the EK15 chassis are designed for more general use. They contain switches to select up to 511 pulse counts before stopping the clock count. The clock counts can be divided down to obtain longer times to fill the register.

Circuits

Figure 54 is a schematic and Figures 55, 56, and 57 show the EK14 printed circuit cards for the speed sense. Figure 58 is a photograph of the fanning strips for attachment to the computer terminal. This function is set for 15 pulses before stopping the clock counting and transferring the clock counts to the hold register. The circuit is composed of MOS components of negative logic. Operation of ths this sensing circuit is similar to operation of the EK15 circuits described below.

The Cambion cards for the converters are shown by Figure 59 and 60. Schematic of these cards are shown by Figures 61 and 62 . Cables for these two digital words terminate in fanning strips as shown by Figure 58.

Pulse Count Circuit Description

The pulse count circuit is contained on two Cambion cards shown by Figures 59 and 60 of the pulse input is conditioned by a dual amplifier and the pulses are counted by 4½ SN 7473 dual J-K flip flops. The number pulses to be counted are set by nine switches connected to the Q and Q not outputs of the flip flops. When the selected number is reached logic stops the clock pulses which are being counted by a digital counter of 15 bits. After the clock count is stopped, the number is transferred to a hold register of 15 bits. The output of the hold register is converted to the IBM 1800 logic by dual inline amplifiers. Figures 61 and 62 are circuit block diagrams illustrating connection of the components and operation of the circuits.

- Pulse Conditioner

  The pulse conditioner is composed of one dual inline 749 amplifier which contains two 709 type amplifiers. One amplifier is used to obtain a rapid rise and high voltage for input to the second stage. The output of the first stage is filtered to minimize the effects of the high frequency clock noise as input to the second stage. The

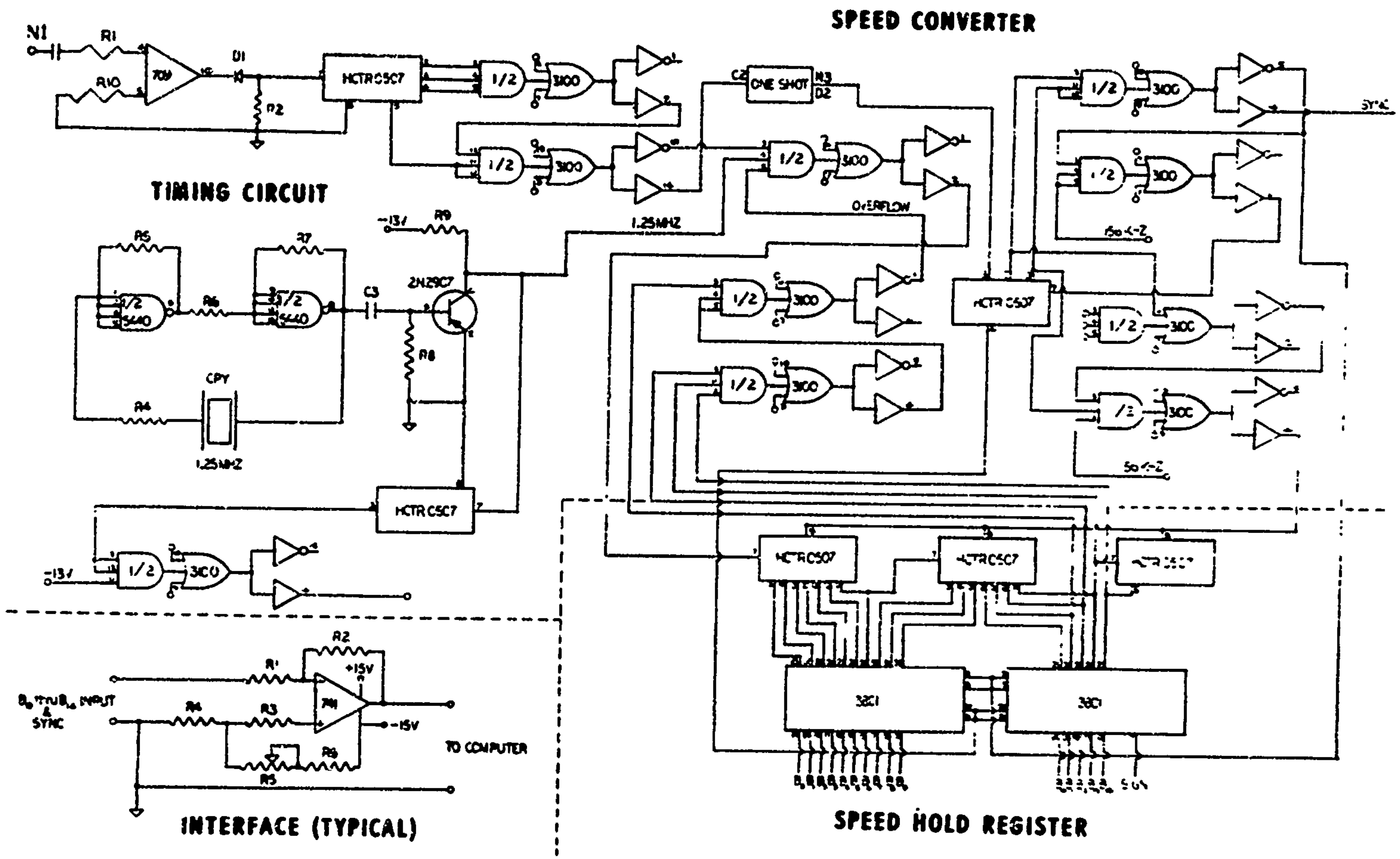


Figure 54. Digital Speed Circuit Schematic

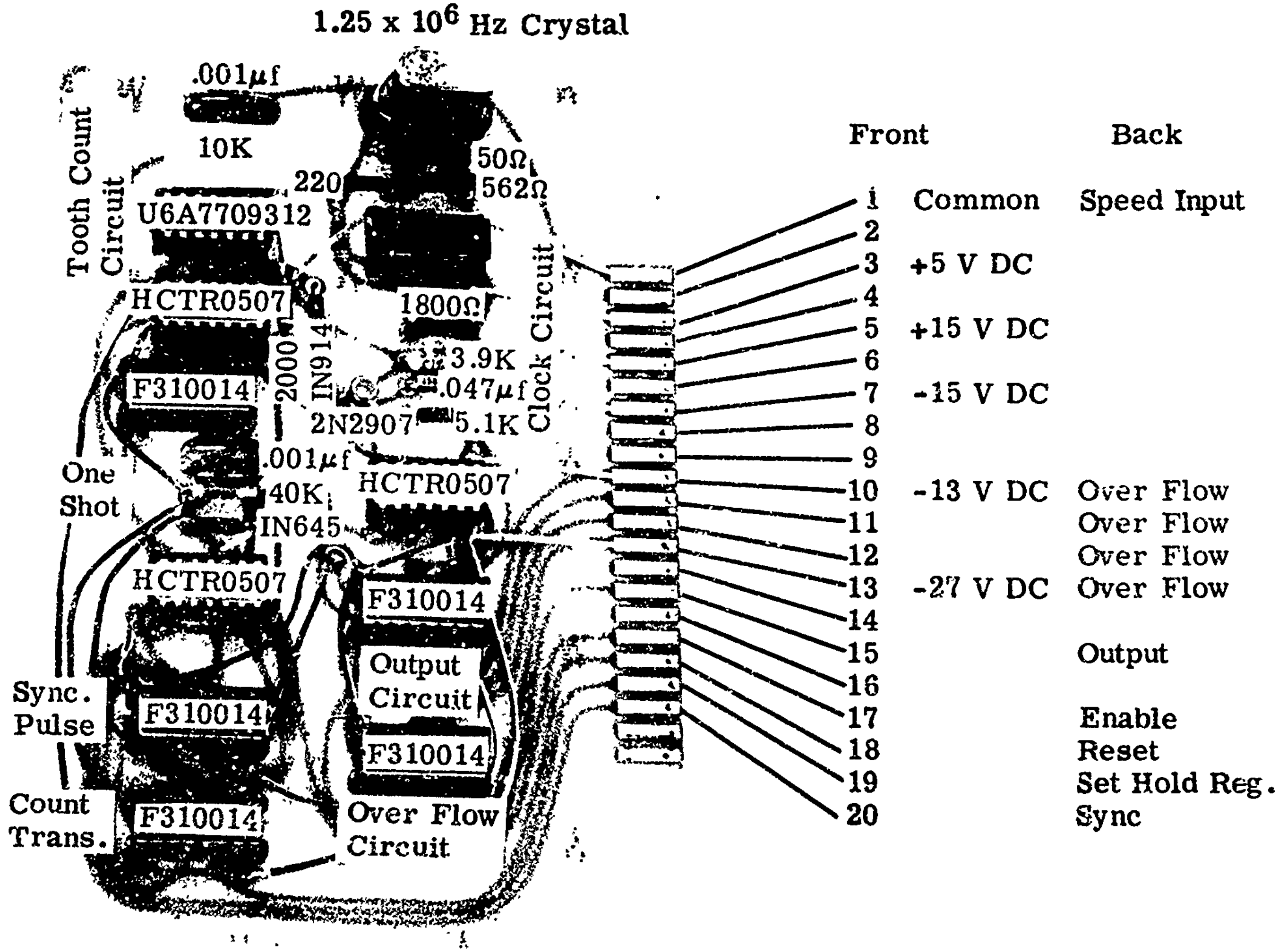


Figure 55 -- Digital Speed Logic Circuit Card

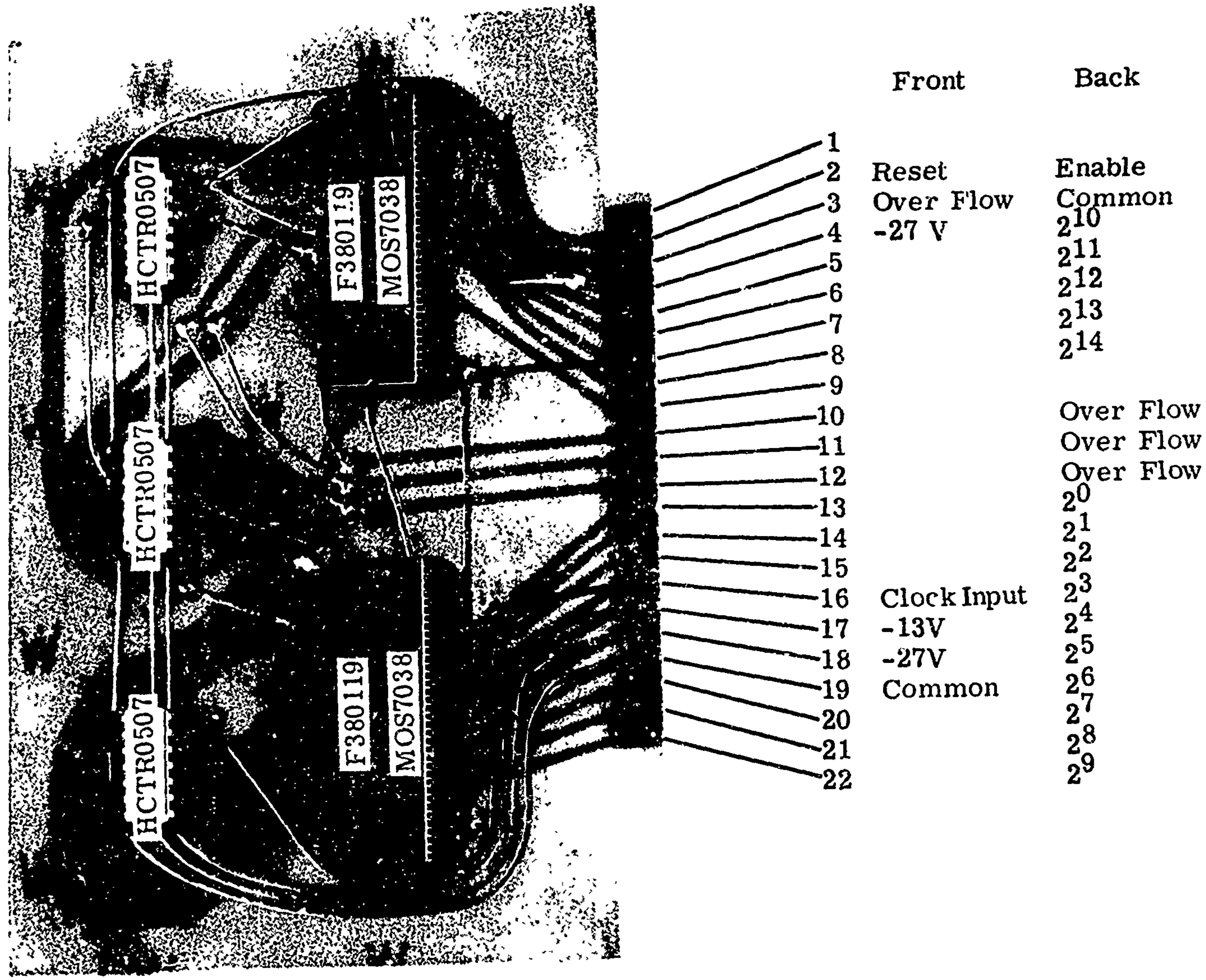


Figure 56 -- Speed Counter and Hold Register

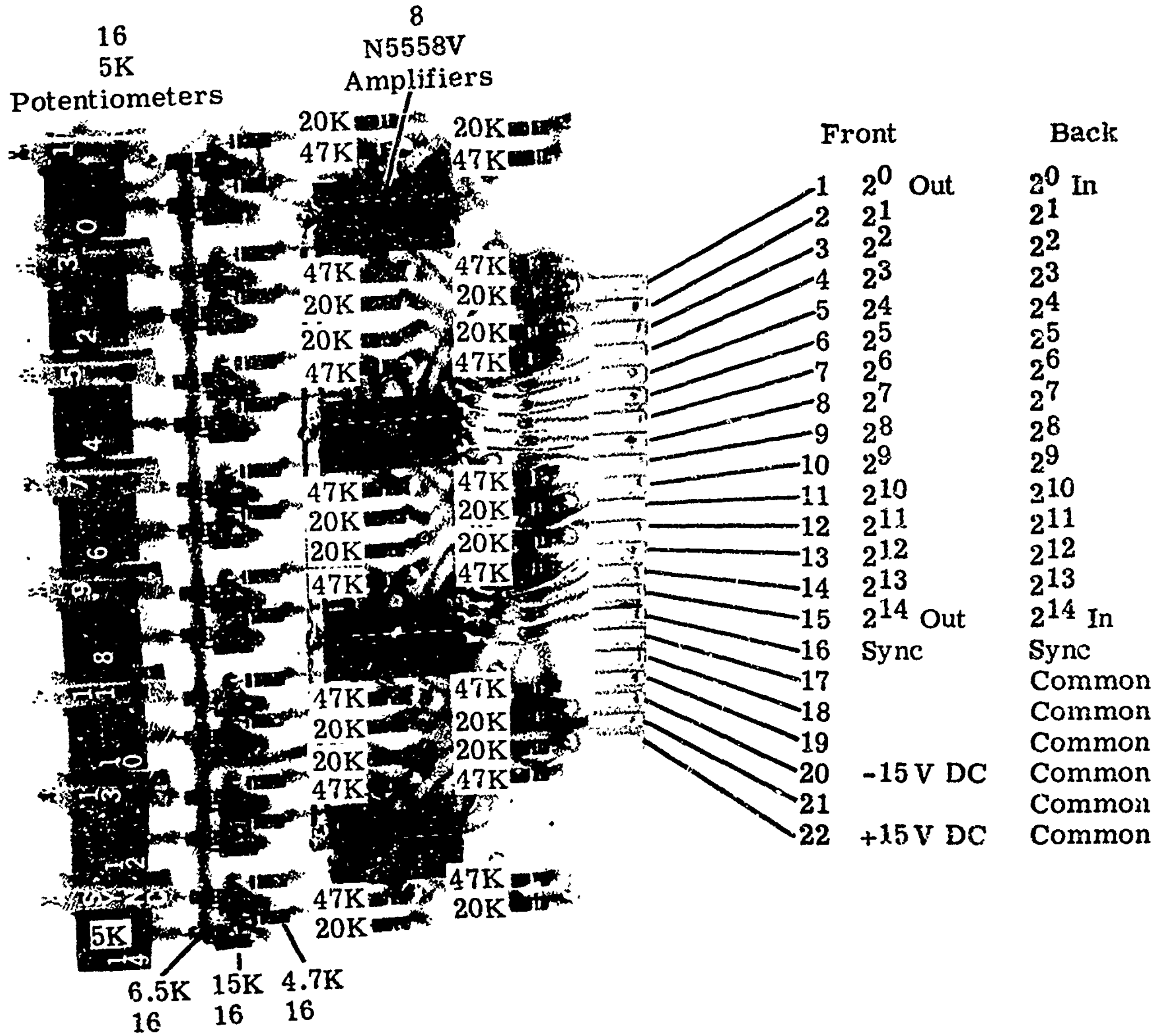


Figure 57 -- Digital Speed Signal Output Card

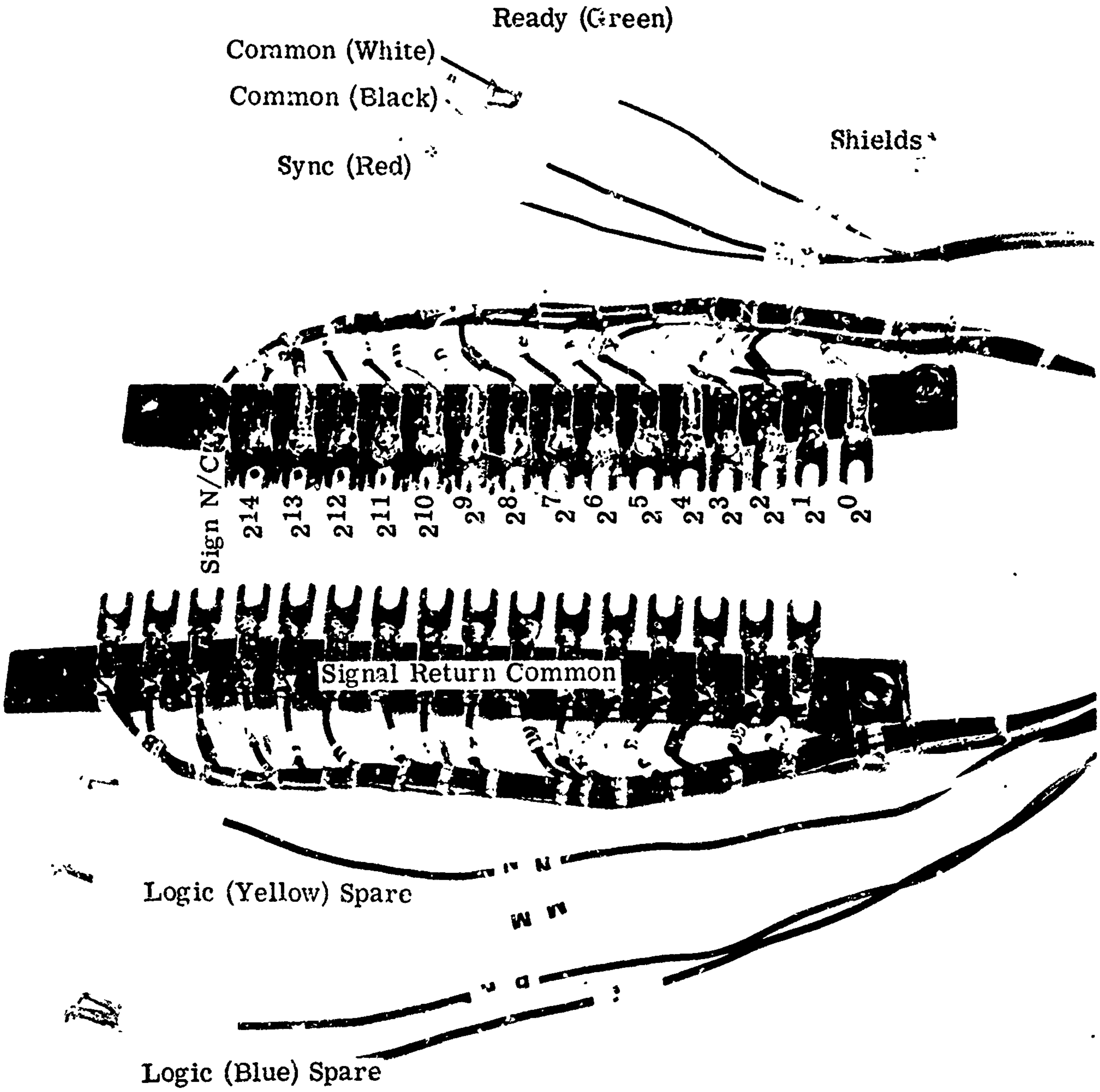
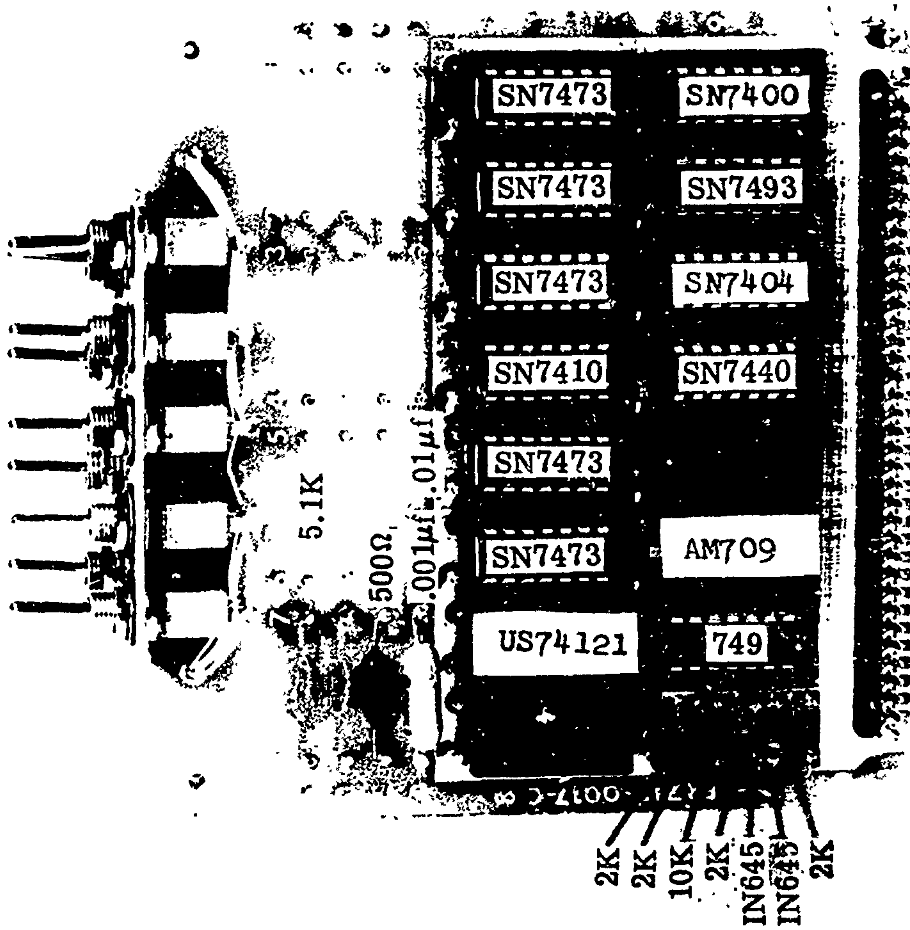


Figure 58 -- Digital Signal Wiring Cable



COMPONENT SIDE			PIN SIDE	
35		COMMON		70
34		COMMON		69
33		+ 5VDC		68
32		+ 5VDC		67
31		- 5VDC		66
30		- 5VDC		65
29		-15VDC		64
28		-15VDC		63
27		+15VDC		62
26		+15VDC		61
25			SYNC	60
24				59
23			TRANSFER	58
22				57
21			1/4 CLOCK	56
20				55
19				54
18				53
17				52
16				51
15	PULSES			50
14				49
13			CLEAR	48
12				47
11			STOP	46
10				45
9				44
8				43
7				42
6				41
5				40
4				39
3				38
2		COMMON		37
1		COMMON		36

Figure 59 -- Pulse Counter and Logic Card

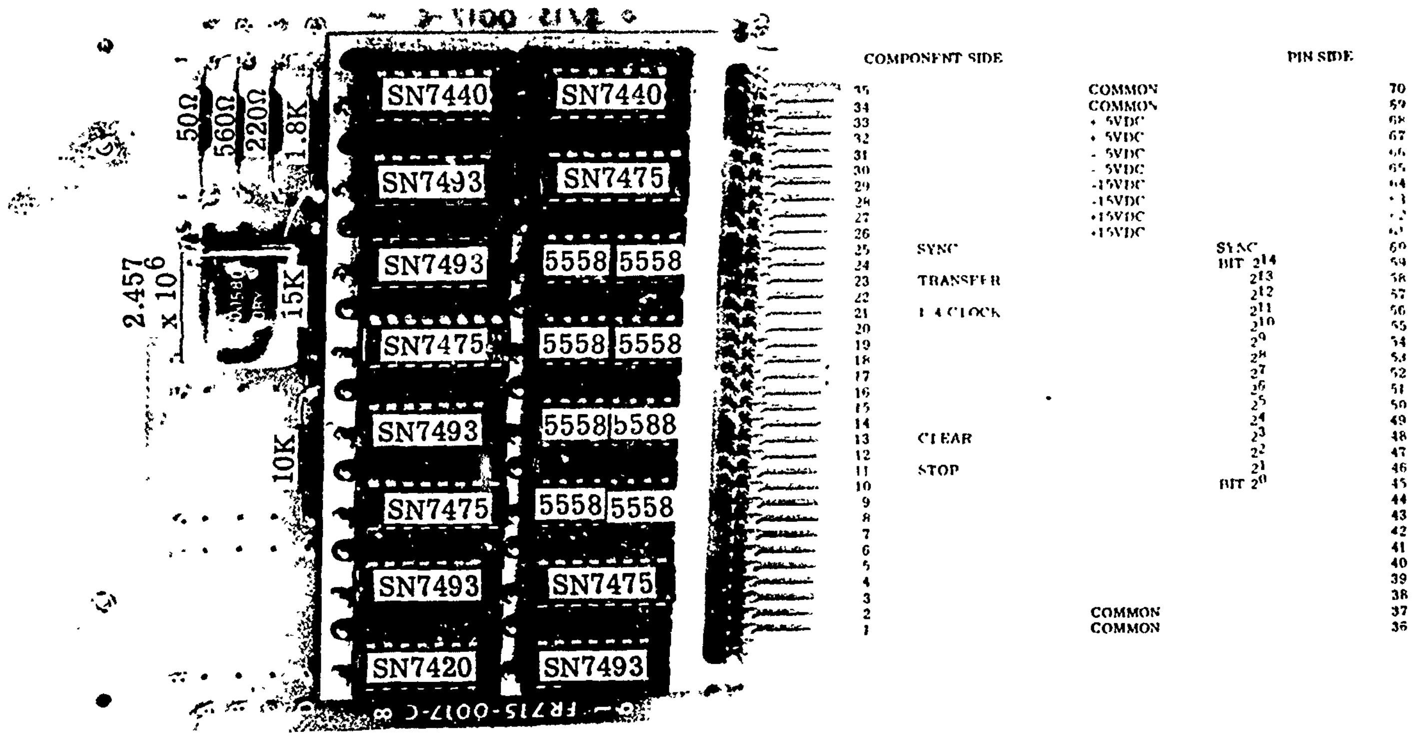


Figure 60 -- Clock Pulse-Count Circuit and Output Amplifiers

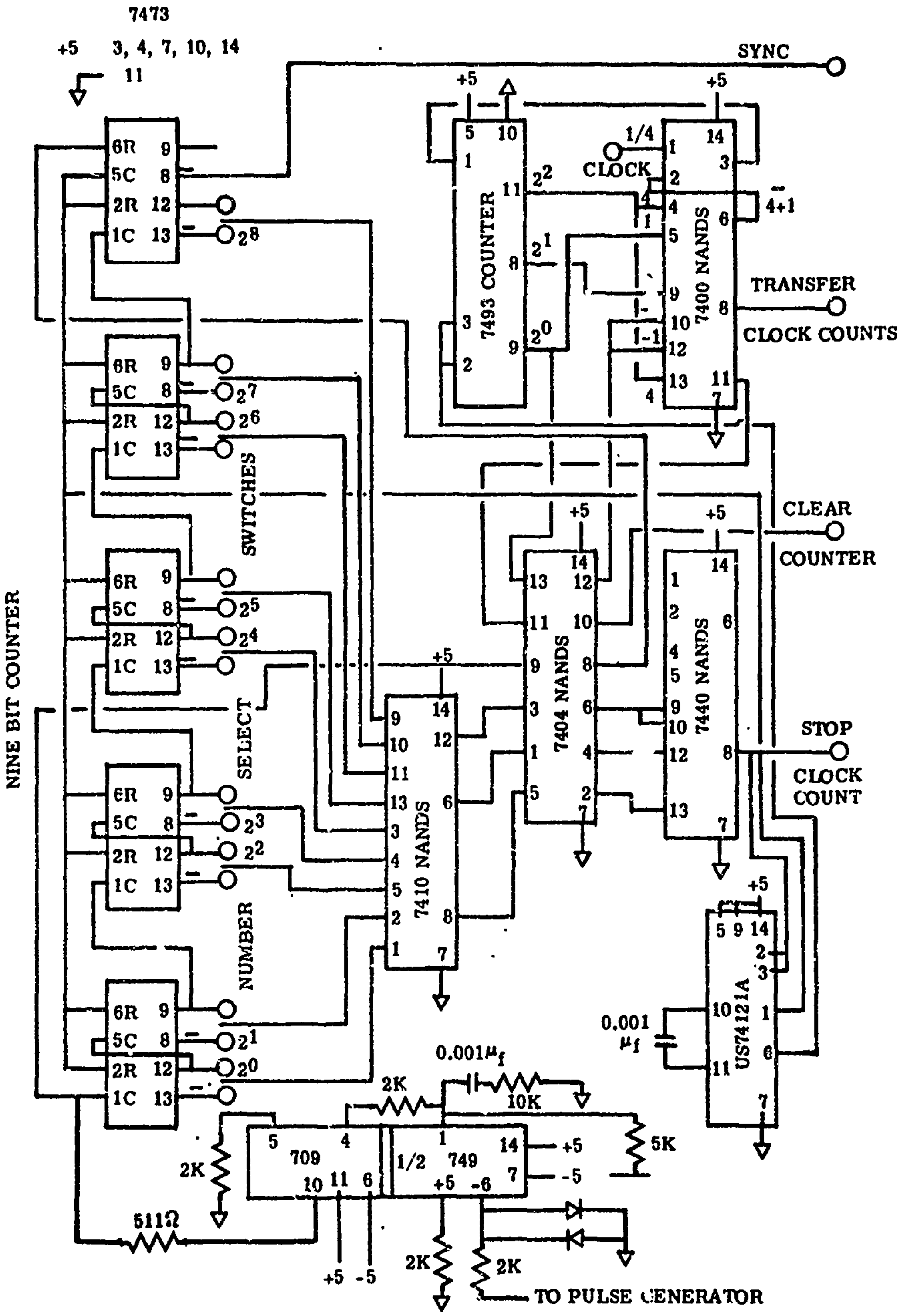


Figure 61 -- Pulse Counter and Logic Diagram

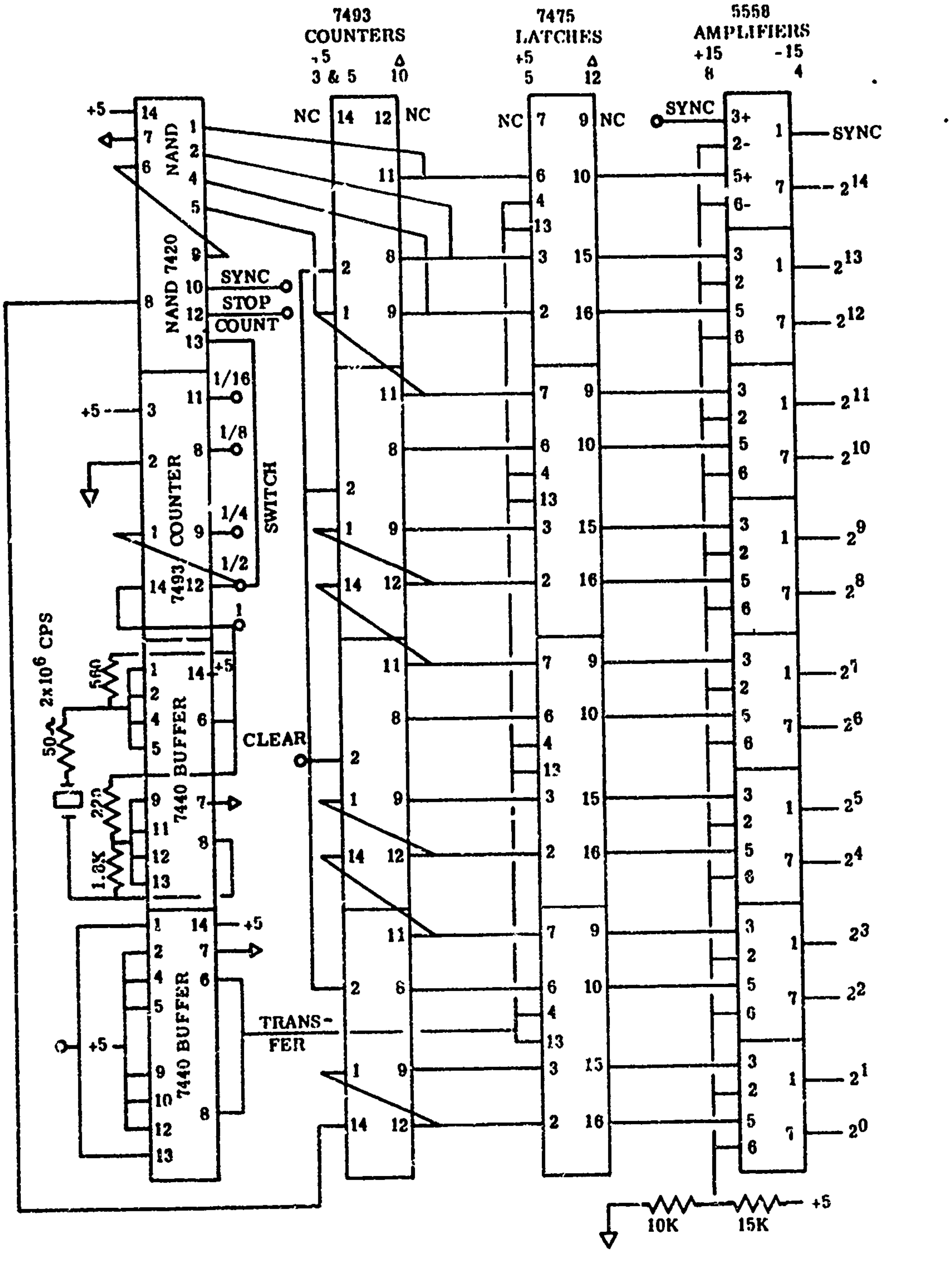


Figure 62 -- Clock Pulse Count Circuit & Output Amplifiers

output of the second stage is limited to positive pulses by a diode and limited to approximately five volts by the five volts excitation voltage. Design values of the circuit components are based on 5,000 pulses per second at very low (0.25) volts and up to 50,000 pulses per second at up to ±40 volts.

- Pulse Counter

The pulse counter is composed of nine J-K flip flops. The primary purpose of the counter is to count electro-magnetic pulses for one revolution of a toothed wheel. Any number of revolutions can be counted to the 511 pulse limit of the nine bit counter. In order to start and stop the count on the same tooth, a number equal to the number of teeth in the wheel or equal to a multiple of the number of teeth is set by the counter selection switches. One tooth space is used for logic transfer and next sequence of counts starts and stops on the next tooth.

The following table indicates the method of setting the count number N_c.

SWITCH NUMBER

	0		1		2		3		4		5		6		7		8	
Logic	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
Number	1	0	2	0	4	0	8	0	16	0	32	0	64	0	128	0	256	0

$\dfrac{0 \text{ FOR}}{Q \;\; N_c - Q_1 - Q_2 \ldots}$ $\quad$ $\dfrac{0 \text{ FOR}}{Q \;\; N_c - Q_1}$ $\quad$ $\dfrac{0 \text{ FOR}}{Q \;\; N_c}$

- Wheel Pulse Count Logic

When the set number is reached all outputs of the switches are at logic "1". The nine (9) inputs are fed into a triple 3-input Nand gate. The three (3) outputs are inverted and fed into half a dual 4-input Nand buffer. The logic "0" thus obtained is fed to Nand logic which stops pulsing of the clock pulses to the clock pulse counter. The output of the 4-input buffer is fed to a VS74121A one shot. The logic "1" signal clears a three bit counter and the logic "0" clears the pulse counter and at the same time clocks a J-K flip flop to Q equal logic "1". The Q not is then logic "0". This becomes the computer sync signal and is also fed to the clock Nand gate to prevent counting.

When the wheel pulse counter is cleared, the stop clock count signal returns to logic "1" but the parallel sync signal prevents clock pulse counting. Also the clear of the 3-bit counter returns to logic "0" and the counter starts to count at $\frac{1}{4}$ the clock frequency. The 0 and 2 bits are fed into one part of a quadruple-2 input Nand gate. The output of this gate is fed into another part of the gate along with the $\frac{1}{4}$ frequency clock pulses. Thus when these two bits are logic "1" the counting stops.

On the second clock pulse at count two the 1-bit is logic "1" and the 0-bit is at locig "0". The 0-bit is inverted and along with the 1-bit is fed through a part of the quadruple gate to transfer the clock pulse count. On the count of threc the transfer signal is off. On the count of four tne not 0-bit and the 2-bit are fed into a part of the quadruple Nand gate to clear the clock pulse counter. At the count of five, both the 0-bit and the 2-bit are logic "1" and the counting is stopped.

When the not tooth or frequency pulse falls, the signal through an inverter clears the sync flip flop to start the clock pulses again.

- Clock Pulses

Clock pulses are generated by a crystal oscillator at 2.247 x 10^6 pulses per second. These pulses are applied to a four bit counter to divide the pulses down by factors of 2, 4, 8, and 16 so that selection of the number of pulses in the count time can be made compatible with the clock pulse counter. The clock pulses are counted for a time interval which is proportional to the reciprocal of frequency. The number is thus proportional to the reciprocal of frequency and the greater number of counts occur at lower frequencies.

Over flow of the clock pulse counter is prevented by stopping the pulse input when the four most significant bits are logic "1". Thus the greatest counter number is 30,710. If it were desired to obtain a count for .040 second which would be 25 cps or 1500 rpm of the toothed wheel, the clock frequency would need to be less than 30,710 x 25 equal 767750 cps. Since the 2.4576 x 10^6 clock can be divided down, the pulses to the counter would be selected from $\frac{1}{4}$ position of the divide counter. The counter will fill in 30710/614,400 seconds or about 1200 RPM. Theminimum speeds sensed without saturation is 4800 to 300 RPM for clock frequency to 1/16 clock frequency respectively. Clock pulse counts are proportional to the reciprocal

of speed. The number represented by the counter is divided into a constant to obtain RPM. A constant of 1.48×10^8 times the clock frequency switch fraction is set in the computer and divided by the pulse count to yield RPM of the toothed wheel when a full revolution is counted.

- Clock Pulse Count Circuit

The circuit is illustrated by Figure 62 Clock pulses at 2.4576×10^6 cps are generated by a crystal oscillator circuit. The clock pulses are fed into a 4-bit counter which divides the frequency down. Output of the 4-bit counter is fed through a switch so that the desired frequency can be easily selected. The pulses along with the overflow signal from half a dual r-input gate, the sync signal and the stop count signal is fed through half a dual 4-input Nand gate. The output of this gate is fed into a 15 bit counter composed of four 4-bit counters.

The count is stopped either by the overflow or when the desired number of teeth has been counted. As explained previously, logic from the tooth count circuit transfers the number in the clock pulse counter to four 4-bit latches and then the counter is cleared.

Output from each latch is fed into an amplifier. The amplifiers are biased by two volts on the inverting input of the amplifier. Thus for logic "1" the output of the amplifier is +15 volts and for logic "0" the output is -15 volts.

EK15 Power Supplies

Figures 63 and 64 are views of the EK15 power supplies. Each voltage is obtained from a separate commercial voltage power supply as noted in the figures. The five voltages ±5, ±15 and the adjustable 0-34 VDC are available for external use at both the front and rear of the chassis. Each voltage is fused for external use as well as fused for internal package use. Figure 65 is a block diagram illustrating the power supply wiring. Voltages of ±15 VDC are used for the isolation amplifiers of the EK14 chassis. Four voltage levels of ±5 and ±15 VDC are utilized for the circuits of the EK15 chassis.

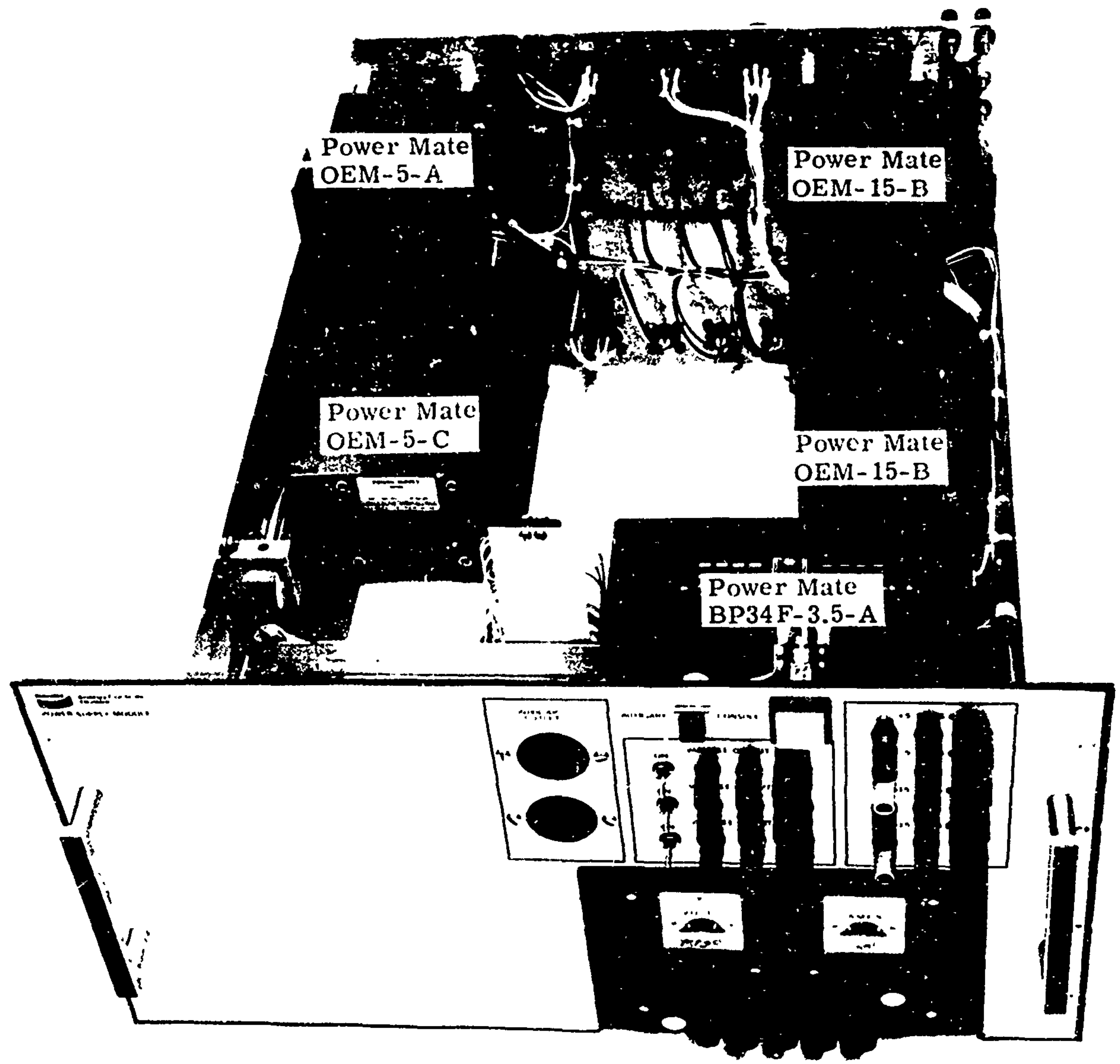


Figure 63 -- Front View of Power Supply Chassis

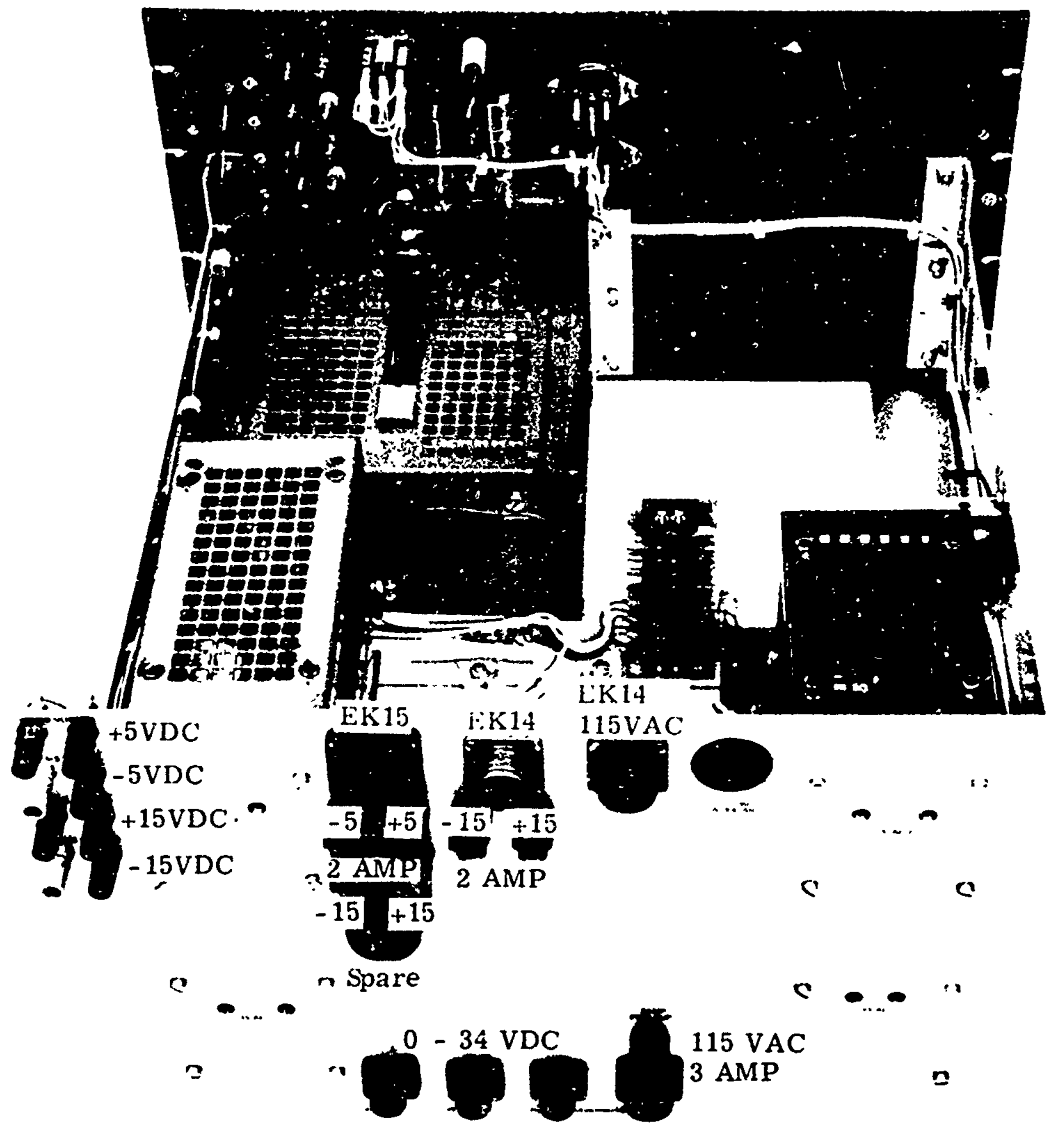


Figure 64 -- Rear View of Power Supply Chassis

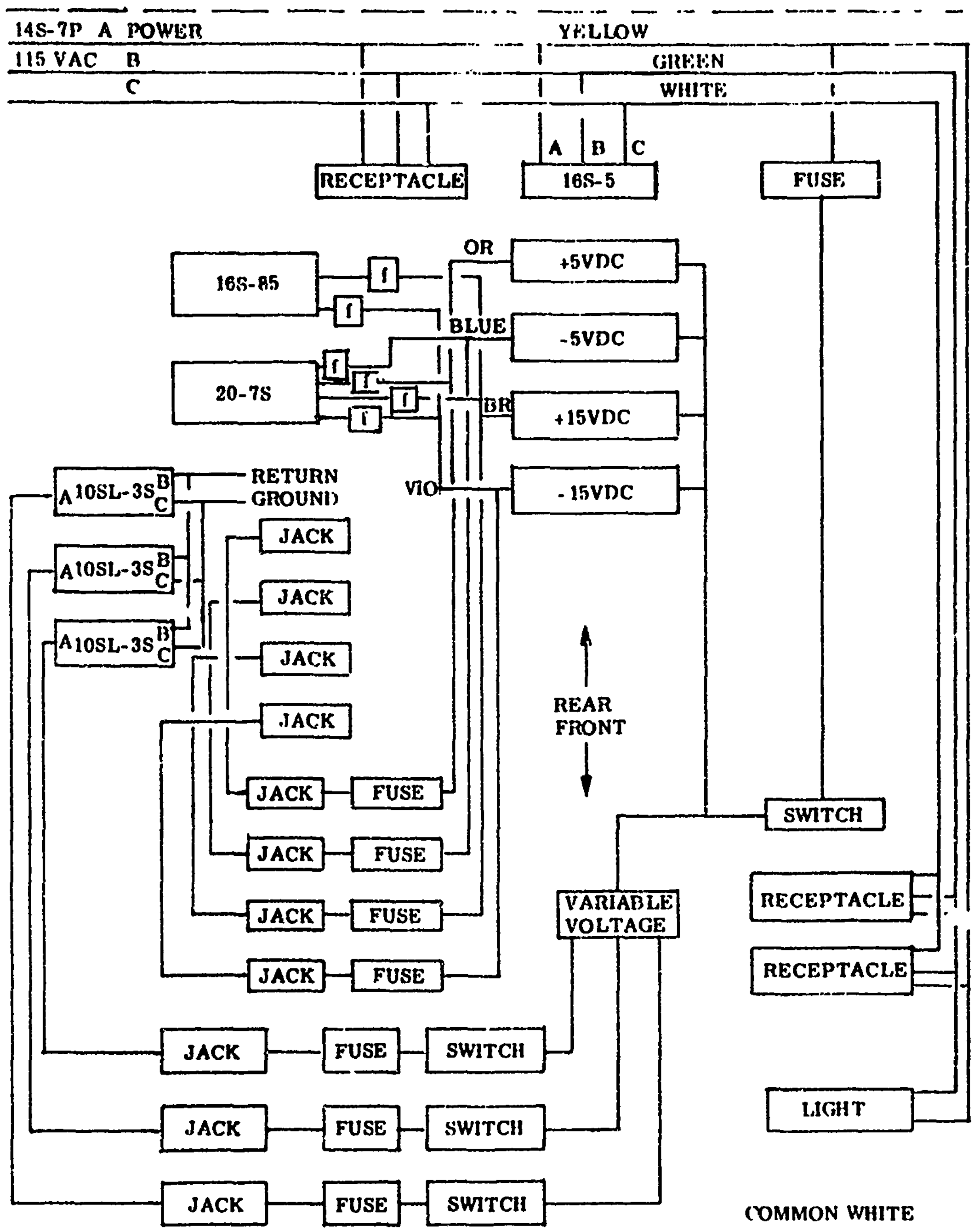


Figure 65 -- Block Diagram of Power Supply Wiring